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OTS:

**A Technique for Testing Heart Function  
by Analysis of its Vibration Spectrum**

**UNPUBLISHED PRELIMINARY DATA**

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## FORWARD

This progress report on NASA Research Grant N<sub>S</sub>G-289-62 [REDACTED] [REDACTED] was prepared by members of the Heart Research Staff of Cedars of Lebanon Institute for Medical Research, Los Angeles and Telecomputing Services, Inc., Panorama City, California. Authors of the report [REDACTED] were Dr. C. M. Agress, Principal Investigator; Dr. Harley M. Estrin, Research Cardiologist; Dr. Daniel J. Bleifer, Research Cardiologist; Dr. Shigeo Nakakura, Research Physiologist; Stanley Wegner, Research Physiologist; Lyman Beman, Electronics Engineer; and Palmer R. McInnis, Consultant and Technical Editor. The authors wish to express their appreciation to Carol Russell and Trudy Mandel for their valuable assistance in manuscript preparation.

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The research program discussed in this document is concerned primarily with a technique for testing heart function by analysis of its vibration spectrum. The overall intent of the program is to develop a method for readily assessing the functional status of the heart.

During the past two years we have witnessed rapid growth and significant advances in the study of precordial vibrations. The interest which stimulated these advances arose from the need for a simple technique which would permit accurate assessment of the heart's function. Such a technique, freed from direct intravascular or intracardiac monitoring, would provide a simple, practical method of evaluating cardiac performance in the environment of an office, laboratory, spacecraft, or in any environment in which the subject's freedom is of importance.



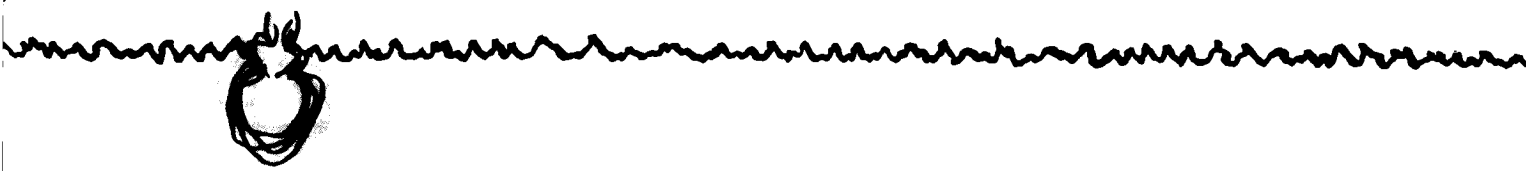
Our investigations thus far under Research Grant N<sub>S</sub>G-289-62 have provided a better understanding of 1) the physical principles and physiology underlying the transfer of cardiac vibrational energy to the chest wall, 2) the development of instrumentation and techniques required for heart vibration data recording, 3) the interpretation of cardiac vibrational energy, and 4) the development and implementation of semi-automatic methods for the measurement and computation of heart function data. Of great interest, was the finding that the vibrational waves recorded from the chest wall showed a high degree of correlation with hemodynamic events. It has been found that measurement of the phases of isometric contraction, ejection, systole and diastole could be obtained from the precordial vibration tracing with an accuracy as good as that realized with direct cardiac catheterization. Further, comparisons of these phase intervals under stress procedures in human and animal subjects show significant changes which serve to differentiate the normal from the cardiac injured subject. These changes correlate well with other physiologic parameters during maximum stress. A further means of evaluation is based on the measurement of cardiac vibrational energy level during specific phases of the cardiac cycle. These measurements have shown consistent changes during stress and may well provide a means of determining cardiac mechanical force. Recent experimentation



has also shown that the vibrocardiogram will provide a method of measuring relative stroke volume, thereby yielding a measurement of cardiac output. These findings are now being compared with known methods of cardiac output and heart force determinations and, in preliminary experiments, have shown excellent correlation.

The proposed research activity is an extension in the investigation, development and application of methods for assessing the functional status of the heart by analysis of its vibration spectrum. As a part of this effort, plans will be implemented for the correlation of vibrocardiogram data with all other available means of heart monitoring. Automatic computer techniques, to the extent possible, will be employed for these correlative analyses and will include methods for handling experimentation data on both normal and abnormal human and animal subjects.

Under the proposed program continuation, data will be obtained and processed on subjects under such stress conditions as exercise, hypoxia and acceleration (g) loads. With respect to the latter stress condition, cooperative programs have been instituted with NASA's Flight Research Center at Edwards, California and with the Human Centrifuge Laboratory of the University of Southern California for obtaining vibrocardiograms on subjects exposed to g-loads.

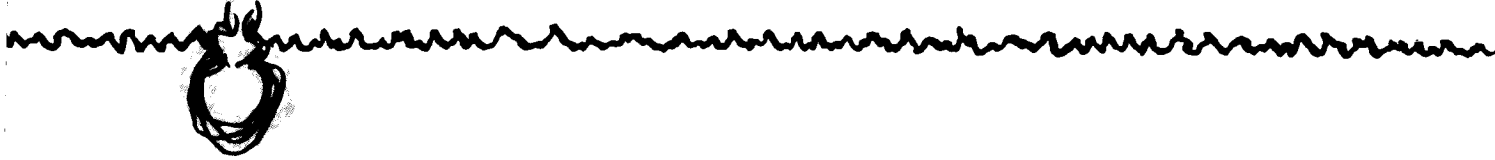


This activity has been coordinated with NASA officials at the Flight Research Center as well as with the appropriate research grant administrative officials at NASA's Ames Research Center, Moffett Field, California.

In addition, the proposed continuation of research effort will provide correlation of the vibrocardiogram with other techniques. In particular, apex cardiography, accelerography and kinetocardiography will be studied in an effort to consolidate the wide spread ramifications which are taking place in this field.

It is felt that the Research Laboratory at Cedars of Lebanon Hospital is uniquely well staffed and equipped to continue the heart research program outlined in this document. By virtue of the Laboratory's experience under the present NASA Grant, its participation in several previous heart research programs, its eminently qualified staff and its equipment capabilities, we are confident that the proposed continuation of these research efforts will be highly successful.

For the required computer programming and data processing operations, we will continue to utilize the facilities of Telecomputing Services, Inc. of Los Angeles. The firm (TSI) possesses a wealth of applicable experience and has worked



as an integral part of our research team; providing data systems engineering, data reduction, mathematical analysis and automatic computer services as outlined in our original proposal to NASA dated 1 November 1961.

In light of the desired NASA funding, it is significant to point out that the proposed efforts will optimally employ the laboratory equipment, instrumentation systems, experimentation techniques and data processing methods which — to a large extent — were developed and proven utilizing the funds made available under NASA Grant N<sub>5</sub>G-289-62. Thus, in terms of technical competence and research procedures, the specific experience and background acquired by the Laboratory and Telecomputing Services, Inc. under the present NASA Grant will be brought into full focus through the continuation of this research program.

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### 2.1.1 Vibration Recording Transducers

Since the origination of this program, extensive study has gone into the evaluation of various types of precordial vibration recording transducers.\* From this study the desirable qualities of these transducers with respect to the particular application of precordial vibration recording were determined. These qualities include 1) a displacement flat response from at least 2 c.p.s. to 2000 c.p.s. to permit the recording of the total energy spectrum of the heart in a form (displacement) which has been found to be most valuable in our previous studies; 2) a wide dynamic range so that the lower amplitude high frequencies as well as the higher energy low frequencies would be reproduced; and 3) light weight, and minimal dimensions to permit usage on human subjects during stress procedures.

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\*Agress, Clarence M.; Wegner, Stanley; Bleifer, Daniel J.; Lindsey, Alfred; Van Houten, John; Schroyer, Kenneth; and Estrin, Harley M.: The common origin of precordial vibrations. (American Journal of Cardiology - April, 1964; Probably)

Since none of the available transducers fulfilled these qualifications, further development of an "ideal" transducer was necessitated. To this end, engineers of Ling Temco Vought, Inc. have worked with members of our staff and Telecomputing Services, Inc. to develop a transducer with the desired specifications. Two models have thus far

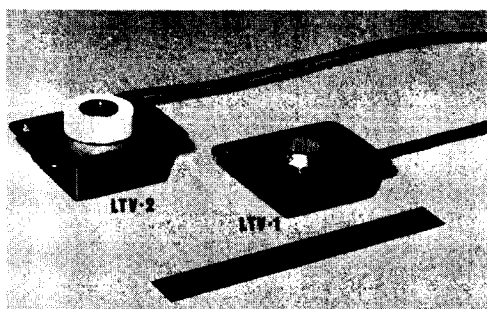


Figure 1

been utilized in our experiments. These units, shown in Figure 1 as LTV-1 and LTV-2, are transistorized for minimal size, have a frequency response of 1.6 to 3000 c.p.s. ( $\pm 3$ db) and a dynamic range of 90 db. Both of these units have been used

in our experiments with gratifying results.

A third model of the LTV transducer was announced during the preparation of this report. The new unit, designated LTV-3, incorporates a number of suggestions from our staff. Following are several points with relation to the new microphone shown in Figures 2 and 3:

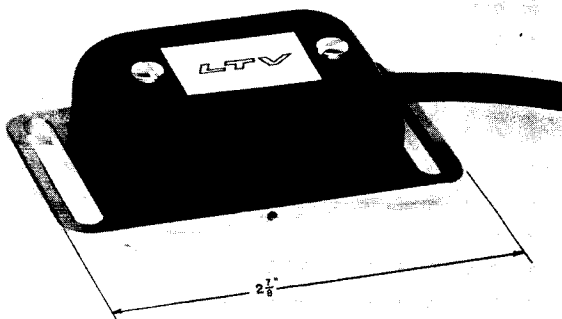


Figure 2

\*The height has been reduced to  $3/4$ ", plus pad. The microphone projects  $3/32$ " from the base plate and the tentative coupling pad is  $1/4$ " thick silicone rubber.

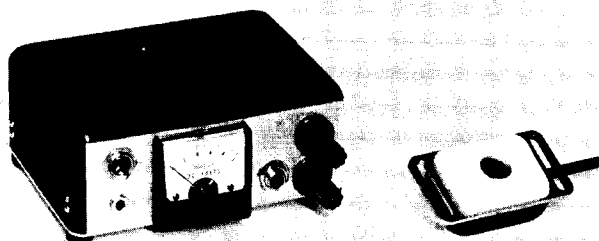



Figure 3

\*The case is made of chrome plated brass with an anodized aluminum cover. The microphone diaphragm is now stainless steel and is additionally protected with Mylar as before.

\*To avoid overloading, the sensitivity has been reduced approximately 15 db. The noise level remains low as before.




\*An emitter follower has been incorporated in the unit which provides a low impedance, 600 ohm output thus reducing cable noise and hum pickup. The output voltage is not affected by this addition.

\*The low frequency cutoff is adjustable within limits and can be readily modified for acoustic equalization.

\*The battery box (shown in Figure 3) has been enlarged for increased battery life (four flashlight cells are used) and a meter incorporated which shows the battery condition and indicates when the unit is switched on. A switch, GR, BNC and phono outputs are provided.

\*A terminal board is provided in the battery case which can incorporate a preamplifier of greater output voltage if required, or electrical equalization — if it is desired to reduce the low frequency amplification in order to better fit the dynamic range of typical tape recorders.



\*The unit can be completely filled with a silicone potting compound to render it impervious to moisture, vibration and similar environmental influences. Also, the diaphragm spacing in the microphone has been doubled to provide greater moisture resistance as well as to control the sensitivity.

#### 2.1.2 Instrumentation Capabilities

The instrumentation from both human and animal experimentation has been greatly expanded at the writing of this document. Our facilities now include a completely instrumented human exercise testing facility, a mobile unit for obtaining vibrocardiographic data from other locations and a completely instrumented animal experimentation system for obtaining all necessary physiologic parameters with greater precision and accuracy. The following material presents a more detailed description of our present instrumentation capability.

### 2.1.2.1 Human Instrumentation Techniques

In an effort to acquaint the reader with the over-all human instrumentation capability of the laboratory, the following diagram is presented:

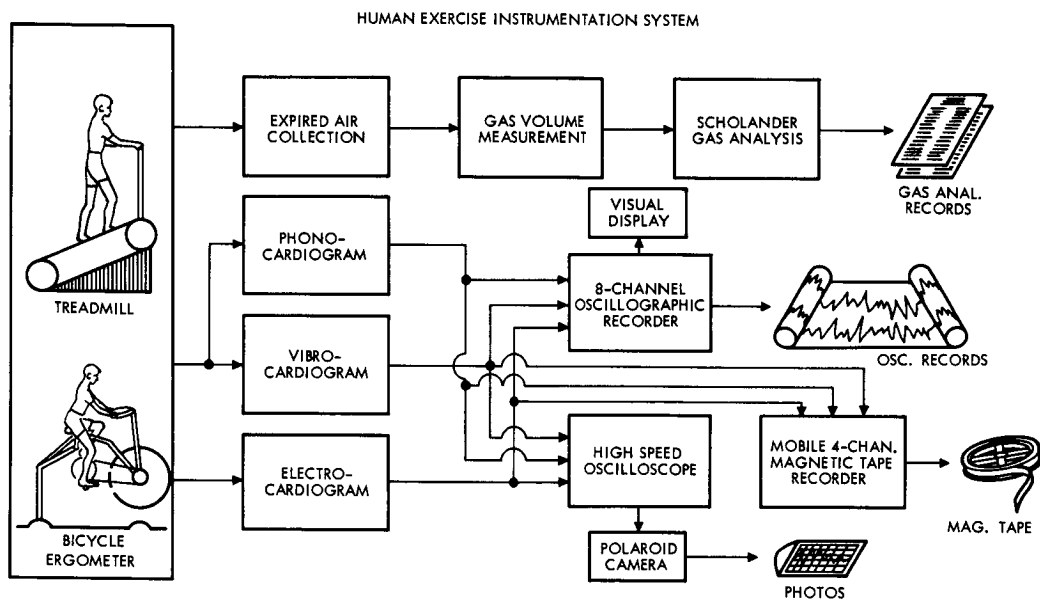


Figure 4

As indicated in the diagram, two types of human exercise tests are currently being performed. One test involves the use of the bicycle ergometer while the other involves a treadmill.

In both types of exercise tests, expired air samples are obtained at various levels of exercise for the purpose of



Figure 5

attending doctor is monitoring various parameters recorded by an Electronics for Medicine 8-channel photographic recorder. Selected data channels are displayed via the two oscilloscopes shown, and for some tests, the cycle counter shown in the upper right is employed as an integral part of the instrumentation system.)

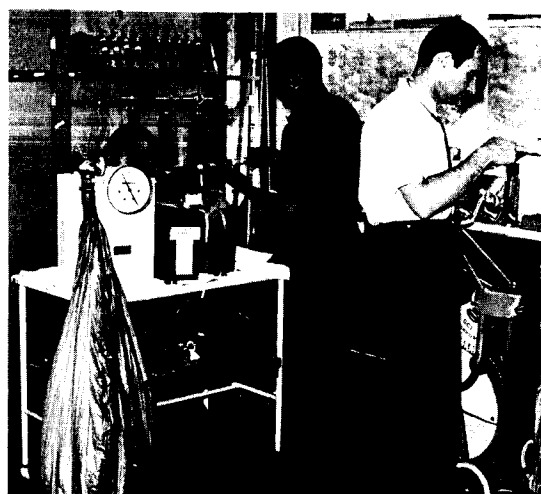
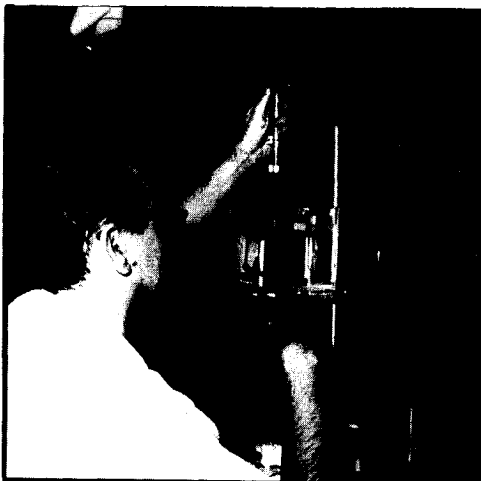


Figure 6

determining oxygen uptake. This is accomplished by allowing the subject to breathe through a one-way valve system (Rudolph valve); the inflow of which is open to room air and the outflow connected to a gas collection bag as shown in Figure 5. (The

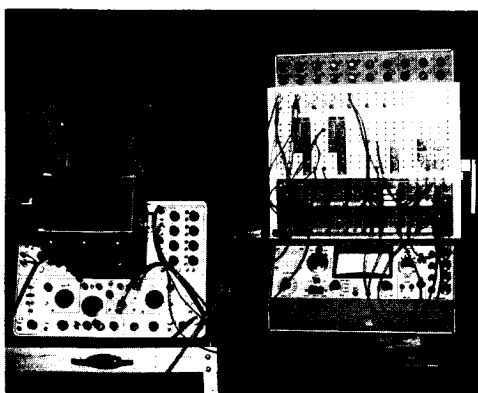
After completing the treadmill or bicycle exercise test, the volumes of expired air samples are measured by "pulling" the air through a dry gas measuring device. The amount of air measured for each sample is displayed on a meter as shown in Figure 6.



During the measuring process, samples are drawn for analysis. These samples are analyzed for oxygen and CO<sub>2</sub> content by use of a Scholander Gas Analyzer, as shown in Figure 7.

Recordings of vibrocardiograms (VbCG) and ECG's are obtained throughout the various phases of exercise and recovery. A Tektronix oscilloscope with

Figure 7 attached polaroid camera is also employed for some tests, as shown in Figure 8. Use of the oscilloscope and attached camera makes available extremely high sweep speeds (500-100 mm/second) to provide a measurement of vibrocardiographic wave intervals with an accuracy of  $\pm 2$  milliseconds.



In addition to the above described means of recording human exercise test data, another recorder has been recently placed in service at the laboratory. It is a mobile

Figure 8



Figure 9

four (4) channel magnetic tape recording unit. VbCG's, ECG's and two additional parameters can now be recorded at the bedside of hospital patients. The unit, shown in Figure 9, also provides the necessary amplifiers and interconnections for amplification and signal modification of four parameters during human and animal laboratory procedures.

Contained in the unit is a four channel FM tape recording system (frequency response DC-2KC); three AC coupled amplifiers (frequency response 0.1 cps to 10KC) for amplification of data parameters; a DC operational amplifier which can be utilized either as a high gain amplifier or for obtaining a first derivative or first integral of any selected parameter; and an interconnection panel which provides input and output from all amplifiers and tape recorders for either monitoring or for coupling with an external recorder.

### 2.1.2.2 Animal Instrumentation Techniques

Data recording equipment for animal experimentation is, generally, the same as that employed for human exercise tests. However, the data input (instrumentation) differs in that intravascular pressures, blood flow, cardiac force and cardiac output are recorded during animal experiments in addition to the routine recordings of phono-, electro- and vibrocardiograms. Also, by use of an Electronics Associates analog computer, processes of mathematical differentiation and integration can be applied to various data before recording and display. A diagram of the overall system is presented below in Figure 10.

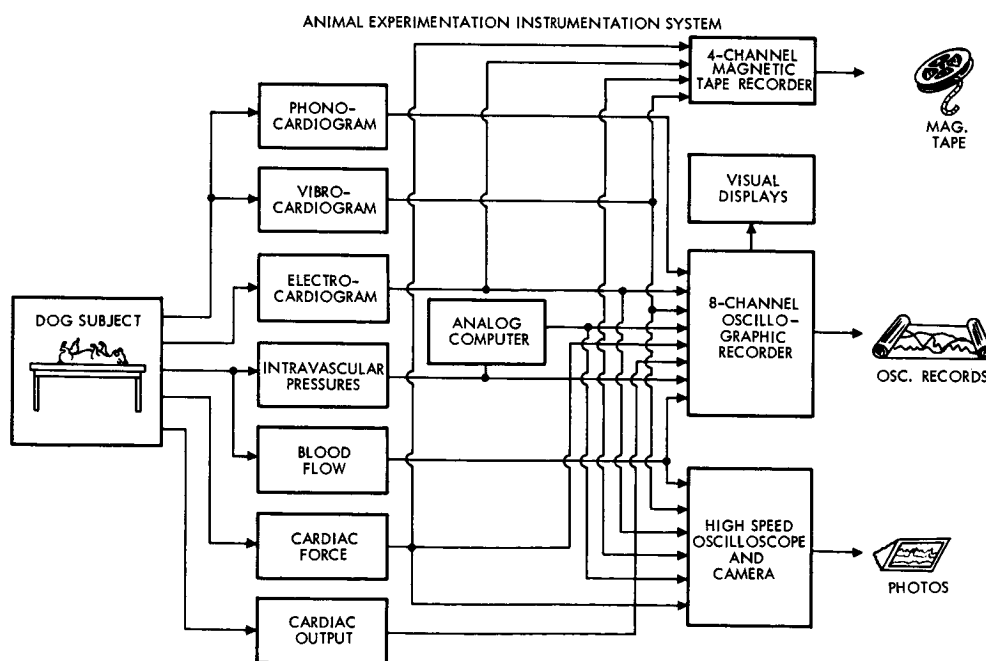



Figure 10




Intravascular pressure measurements are now being obtained by the Statham transducer tipped catheter. This system is advantageous as it eliminates the resonances, motion artefacts, and time delays often encountered with the conventional fluid filled catheter systems. The precise locations of pressure rises and changes in rate of pressure rise are easily identified through the employment of this system.

Instrumentation for accurate measurement of cardiac output has yet to be completed. Two methods are being investigated; the dye-dilution and the pulse pressure techniques. The equipment employed to date for the dye-dilution method was found to be a linear and would not yield consistent results. Since accurate measurements of cardiac output are of extreme importance in our studies, we have purchased more accurate and reliable equipment for this purpose. The second method, involving pulse pressure technique of Jones, et al.<sup>\*</sup>, is being utilized to obtain stroke volume measurements. With this method, a partial time derivative of the root aortic pressure is obtained and indicates relative volume output of the left ventricle per beat. The equipment necessary for

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\*Jones, W. B.; Hefner, L. L.; Bancroft, W. H. Jr.; and Klip, W.: Velocity of blood flow and stroke volume obtained from the pressure pulse. J. of Clin. Investigation, 38:2087-2090, November 1959.




this measurement has been generously donated to the laboratory by Dr. E. E. Eddleman of Birmingham, Alabama; and has been found useful in studying the relationship between stroke volume and the VbCG.

Instrumentation for the instantaneous determination of cardiac vibrational energy has recently been completed by modification of a Ballantine RMS voltmeter. This unit has been adapted to determine the energy level of the VbCG simultaneously with its recording and will be used in both human and animal experimentation.

In addition, circuitry has been developed which will allow the measurement of vibrational energy during the isometric contraction and ejection phases of systole. This equipment provides wave recognition circuitry for the location of the "H", "J<sub>2</sub>" and "L" vibrocardiographic waves, and gating circuitry which permits both energy levels and time between any of these points.\*

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\*Agress, C. M. and Stroud, C. H.: Heart function evaluation by real-time electronic diagnosis of the vibrocardiogram. Proceedings of the 1961 San Diego Biomedical Engineering Symposium.



## 2.2 Data Analysis Capabilities

The methods for vibrocardiographic analysis are based on observations of numerous human and animal experiments performed in this laboratory. These methods represent the major vibrocardiographic factors which have thus far shown a relationship to cardiac function in the normal and abnormal subject. Since these methods of analysis are dependent on the accurate identification of the vibrocardiographic waves, it was desired to provide a means of identifying these waves without the aid of other reference tracings. This has been accomplished by determining the time relationship of the major vibrocardiographic deflections to the "R" wave of the electrocardiogram as illustrated in Figure 11 on the following page.

There is very little overlap in the time ranges of the vibrocardiographic waves as measured from the "R" wave of the ECG, thus permitting accurate identification of each systolic wave point by its time interval from the "R" wave reference.

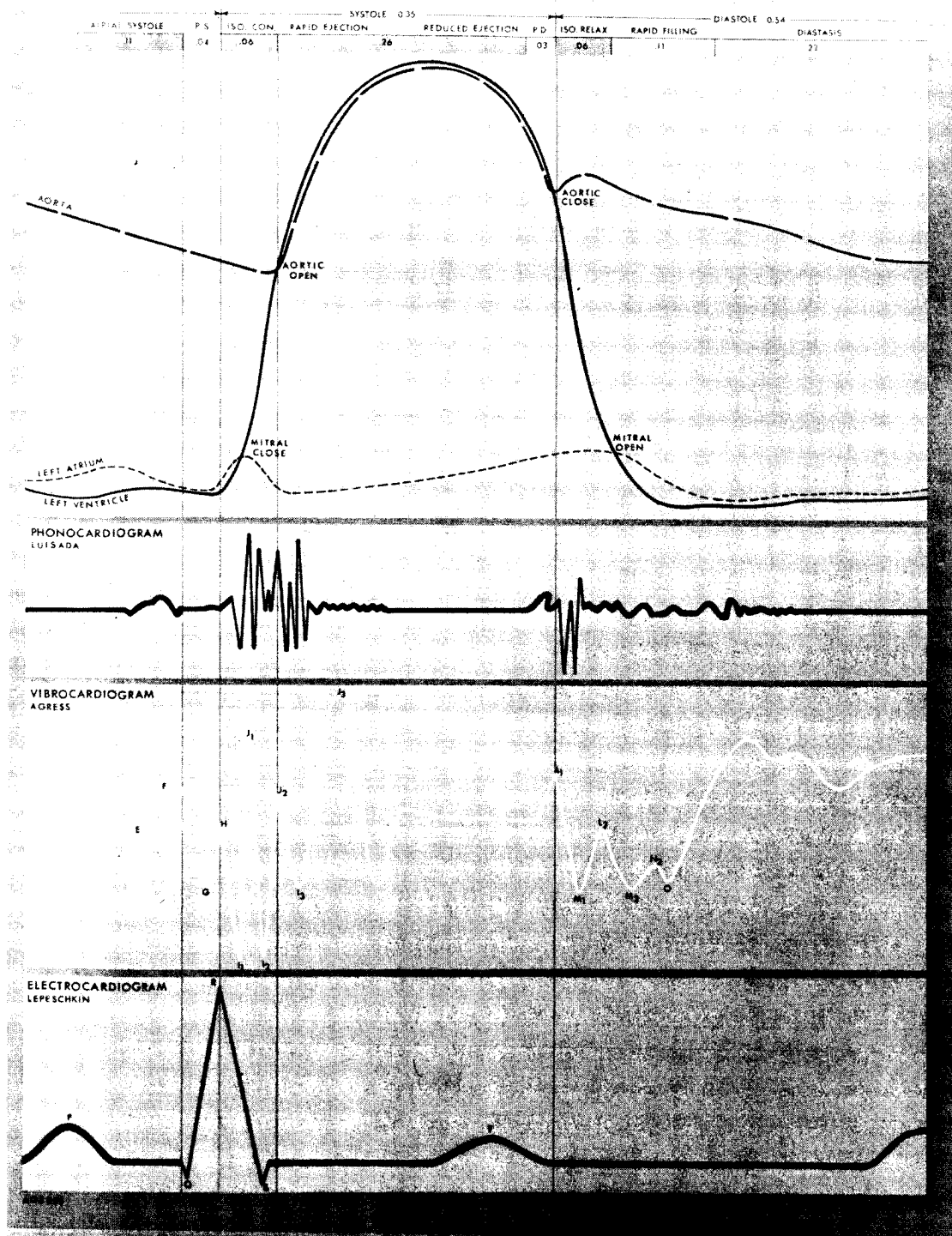


Figure 11


Once the vibrocardiographic waves have been properly identified, the records are then subjected to various data measurement, computation and interpretation methods. Some of these methods are as follows:

A. Ratio of the  $H-J_2/J_2L$  Intervals:

Vibrocardiographic wave points corresponding to the isometric contraction interval ( $H-J_2$ ) and the ejection interval ( $J_2-L$ ) are measured and the ratio,  $H-J_2/J_2L$ , is determined. The change in this ratio from resting to stress conditions is determined. This difference provides an index of cardiac function.

B. Energy Content of the VbCG:

Preliminary studies have indicated that the energy content of the VbCG increases significantly with exercise, and may be closely related to the energy of systolic cardiac contraction. The energy content of the VbCG is assessed by utilizing the formula for kinetic energy, which is  $Ke = 1/2MV^2$ . Since the vibrocardiographic



waves, which represent displacement of chest wall motions, are sinusoidal in nature and are of relatively the same frequency under resting and exercise conditions, any change in displacement of these waves is therefore a direct function of velocity. The square of displacement ( $D^2$ ) can then be substituted for  $V^2$  in the equation. The energy content of the VbCG is then proportional to the area under its squared curve as the mass of the body (M) is constant. Measurements of the energy content by this formula obtained at rest and under conditions of stress can provide a relative index of the changes in cardiac energy involved. A more complete background for this approach will be presented in a later section of this document.

C. Ejection Area of the VbCG:

It has been determined from preliminary animal flow studies that an indication of stroke volume may be obtained by measurement of the area under the ejection

phase ( $J_2$ -L) of the vibrocardiographic curve. This has been accomplished by two means; one in which a line is drawn connecting the peaks of the " $J_2$ " and "L" waves and the area subtended by the vibrocardiographic curve in this region measured; and the other in which a "zero" reference line is connected between two consecutive "H" waves and the area of the vibrocardiographic curve with respect to the reference line is determined in the " $J_2$ " - "L" region.

D. Wave-form Analysis:

Great emphasis has been placed on precordial wave forms by other investigational groups.\* It has been our finding, however, that the shape of the vibrocardiographic curve has considerable variability, dependent on the position of the transducer on the chest, and the position and physical characteristics

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\*Rosa, L. M.: The "displacement" vibrocardiogram of the precordium in the low frequency range. Am. J. Cardiol. 4:191-199, August, 1959.

Rosa, Leslie Michael and Luisada, Aldo A.: The clinical aspects of accelerography. J. of the Maine Medical Association, April, 1962.

of the subject. Interpretations of wave form changes will not be attempted until the physiologic significance of such alterations can be assessed in the controlled experimental preparation.

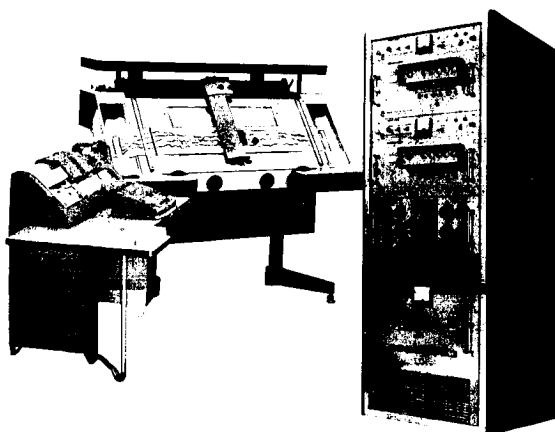
The above briefly described methods of vibrocardiographic analysis represent only those that are most frequently employed. Other, more detailed analyses, will be described later in the discussions concerning Human and Animal Studies.

#### 2.2.1 Data Measurement Techniques

In the above described methods of analysis, reference was made to vibrocardiographic phase intervals, ratio measurements and area under the curve measurements. A brief description of the techniques employed to accomplish these data measurements is appropriate at this point.

Two types of scientific data measurement systems are employed. These systems, commercially known as the DILOG 214 and DILOG 512, are semi-automatic chart measuring machines with automatic high-speed electronic digitizing units.

The DILOG 214 System, shown in Figure 12, is equipped with a unit on which is mounted the 8-channel raw data record containing vibrocardiogram, electrocardiogram, phonocardiogram, intravascular pressure curves, blood flow, etc. The record is back-illuminated by an intensity controlled electric lamp



beneath a ground-glass screen. Handwheel controlled orthogonal measuring crosswires are located immediately beneath the screen and cast a sharp shadow on the surface of the raw data record, thus providing a means of aligning on a reference point (or line) and then traversing the distance

Figure 12  
from the reference point to the data trace being measured. Attached to each crosswire handwheel is an analog-to-digital converter, which feeds a series of pulses to the digitizing unit of the system. The digitizer is a dual (X, Y) indicating accumulator which counts and stores sequential electrical pulses, originating from the system console. When signaled by the system's operator, the digitizer "reads out" the accumulated values to an IBM Card Punch, where the chart measurement is recorded in punched card form for later input to an electronic computing system. Accuracy of trace deflection measurements utilizing the DILOG 214 system is  $\pm .005$  inch. The system permits the measurement of several hundred points per hour by an experienced operator.

The operational characteristics of the DILOG 512 System are quite similar to those described above for the DILOG 214. However, the DILOG 512 is a more versatile system.

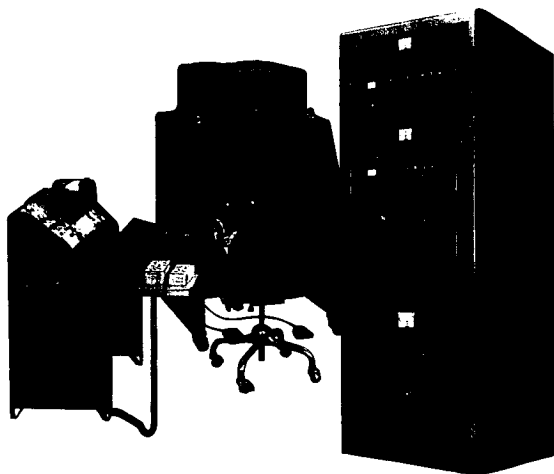


Figure 13

Shown in Figure 13, the system is designed to handle all types of raw data records including film and paper; translucent, transparent or opaque. In addition, the system permits magnification of the raw data record at 2X, 4X and 11X power. This system has proved to be of

outstanding value for the measurement of cardiac data recorded on previously mentioned Polaroid camera film. Improved accuracy ( $\pm .00037$  inch) over the DILOG 214 has been necessary for several of our studies.

Both of the above described data measurement systems are located at the Los Angeles Data Center of Telecomputing Services, Inc. (TSI). In carrying out the required data measurement operations, TSI's personnel maintain close coordination with our laboratory personnel. Each record to be measured is carefully discussed so as to insure the desired accuracy and completeness of processed data.

Data measurement capability of TSI also includes an automatic means of digitizing analog data recorded on magnetic tape. Thus, the magnetic tapes produced by the Dacord 4-channel Recorder at our laboratory can be readily digitized and computer processed through the employment of TSI's services.

On a few occasions, TSI has also provided services for the spectrum analysis of vibrocardiographic data recorded on magnetic tape. We visualize a need for occasional data measurement services of this type in the future.

#### 2.2.2 Automatic Computing Techniques

Due to the mass of data generated by our experiments, automatic computing techniques are essential to this research program. The speed, accuracy and versatility of electronic computers provides a means of eliminating a large amount of manual time, and the amount of time saved is spent in carrying out more research.

A variety of computer programs have been developed and implemented in support of our data requirements. These programs include, but are not limited to the following:

- \* Scaling and linearization of measurements taken from our paper chart raw data records.
- \* Computation of vibrocardiographic time intervals and corresponding deflections along with cardiac cycle phase ratios.
- \* Computation of area under the raw data curve.
- \* Computation of data curve rate of change and slope characteristics.
- \* Statistical analysis of physiological data utilizing least-squares polynomial curve fitting computer programs.
- \* Automatic time phase correlation of physiologic data parameters.

The above computer programs have been prepared and implemented utilizing the services of TSI. Thus far, these programs have involved the use of TSI's IBM 1401

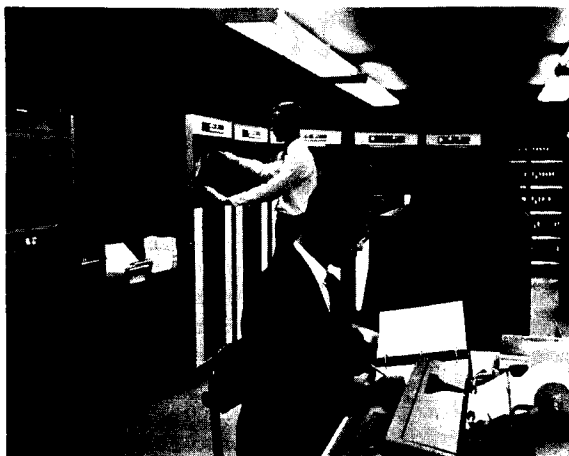



Figure 14

computing system shown in Figure 14. As the size and complexity of these computer programs increase, TSI is prepared to offer computing services on a larger and higher speed computing system; the IBM 7094.



TSI's mathematicians, statisticians, computer programmers and data analysts work as an integral part of our research team in developing the required computer programs and associated operating procedures.

### 3. EXPERIMENTATION RESULTS

The material contained in this section describes the results obtained from human and animal experimentation during the period of NASA support and represents the basis for the proposed continuation of this research program. The first part deals with animal studies and provides a background and rationale for the vibrocardiographic measurements made in the human. Then, in the second part (subsection 3.2), results are presented as obtained from normal and abnormal human subjects under various levels of exercise and indicates the correlation of vibrocardiographic data with other physiologic parameters.

#### 3.1 Animal Studies

Four major areas are discussed for these studies. First, the correlation of vibrocardiograms with hemodynamic events in animals under resting conditions and under the imposed stresses of exercise. Vibrocardiographic and hemodynamic changes under these conditions are described. Second, the effects of hypoxia are discussed followed by a discussion concerning cardiac injury. And last, a discussion is presented concerning various preliminary experimentations that have been conducted in support of strain gauge arch, flow and heart energy transfer function studies.

### 3.1.1 Correlation of Vibrocardiogram, Phonocardiogram, Electrocardiogram and Pressure Pulses

Precordial vibration recording techniques have received increasing attention in recent years, particularly because of their promise of yielding an external method for timing the mechanical events of the cardiac cycle. Previous studies by this and other groups have demonstrated that precordial vibrations provide a reliable means of identifying the individual phases of the cardiac cycle.<sup>1-12</sup> The purpose of this study was to determine as accurately as possible the relationship of the vibrocardiographic waves to hemodynamic events utilizing precise instrumentation and recording techniques.

In addition to studying the conventional pulse pressure curves, experiments were also devised to study the relationship of the VbCG to the time derivatives (rates of change) of the pressure curves, the ventricular "force" recordings and to aortic flow measurements.

An LTV capacitance microphone (described earlier in Section 2.1.1) was used for recording precordial vibrations. The microphone had a flat response from below 2 cps to over 1000 cps. The attenuation rate below two cps is about six db/octave. The transducers for recording intravascular pressures were the Statham SF-1 strain gauge catheters, in

which the sensing element is located at the catheter tip. This system was found advantageous in that it eliminated the time delays, motion artefacts, and resonances often encountered with the conventional fluid-filled catheter systems. Ventricular force recordings were made using the Waltham-Brodie strain gauge arch,<sup>13-14</sup> and the method of Jones, et al,<sup>15-17</sup> was employed to measure aortic flow. In order to obtain the time derivative of the pressure curves, a Dymec operational amplifier was used. Higher order derivatives were determined by means of an EAI analog computer. The recording instrument was a Tektronix No. 565 oscilloscope with a polaroid camera attached to its face.

Eighteen dogs were used in this study. They were anesthetized with intravenous pentobarbital (30 mg/Kg), placed in the dorsal decubitus position, and the microphone was coupled directly to the left fourth interspace near the sternal edge by means of an elastic strap, as shown in

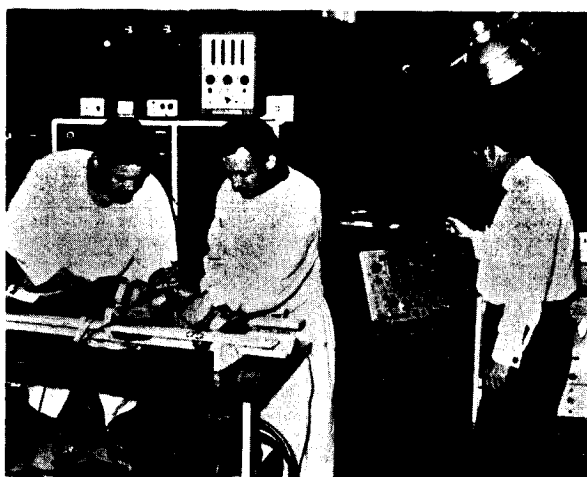
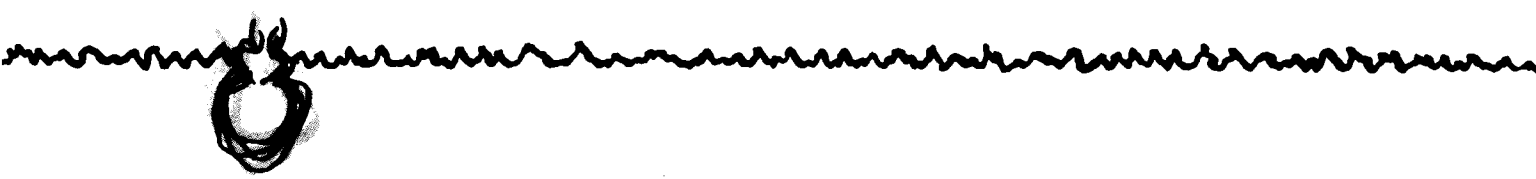


Figure 15

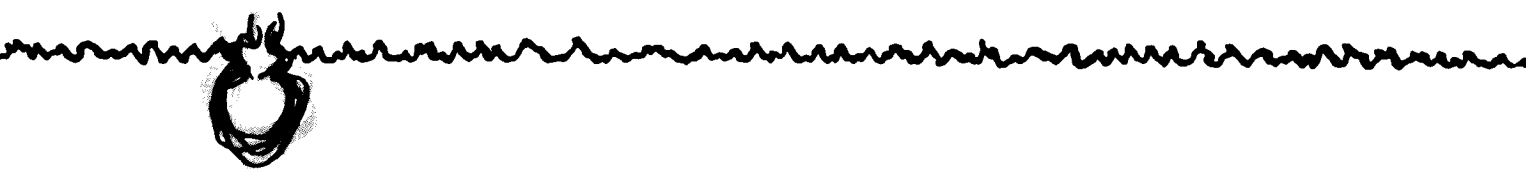
Figure 15. Catheters were inserted into the left ventricle and aorta through the left and right carotid arteries. The direct vision trans-bronchial technique (bronchoscope) was used for left atrial catheterization.



Right atrial, ventricular and pulmonary artery pressure curves were obtained via the left jugular vein. Lead II of the electrocardiogram was monitored in all experiments.

In four dogs, the strain gauge arches for obtaining ventricular force recordings were implanted in the following manner: A mid sternal thoracotomy was performed and the arches sutured to the myocardium near the apex of both ventricles and oriented in the longitudinal axis of the chambers. The lead wires from the arches were passed through the chest in the second left interspace. After a week's recovery, the animals were anesthetized, the transducer tipped catheter passed to the root of the aorta for obtaining pressure and flow curves, and simultaneous recordings made of ventricular force, aortic pressure and flow, the vibrocardiogram and the ECG.

The outputs of the microphone, pressure transducers, force gauges, flow meter and electrocardiogram were photographed from the oscilloscope using sweep rates of 500 (20 msec/cm) and 1000 (10 msec/cm) millimeters per second, permitting measurement accuracies of better than two milliseconds (msec). At these high sweep rates, only the initial phases of systole could be displayed on the oscilloscope face. In order to study the latter phases of systole, a delayed sweep mode was used in which the R wave of the ECG triggered a variable delay circuit, which would initiate the sweep



after a pre-set duration. This interval varied with the animal's heart rate and was adjusted so that the latter phases of systole appeared on the oscilloscope. Raw data measurements were made directly from the photographed image and computer processed.

#### 3.1.1.1 Results - Left Heart

Figure 16, presented on the following page, illustrates a photographic record of aortic pressure (AP), vibrocardiogram, (VbCG), left ventricular pressure, (LVP) and ECG traces and shows the general relationship of the VbCG to left heart pressure phenomena in one complete heart cycle. Figure 17 shows the same parameters at a sweep speed of 500 mm/sec. and Figure 18 at a speed of 1000 mm/sec. In these figures, LVP and AP were recorded independently. The repetitive character of the curves is illustrated in Figure 19, where 20 consecutive beats are recorded on the oscilloscope in full inspiration and expiration. In those experiments in which left atrial and left ventricular pressures were simultaneously recorded with the VbCG, it was often impossible to determine the "cross-over" point of the two curves as the pressures were identical immediately preceding and more than 20 msec. after the onset of ventricular

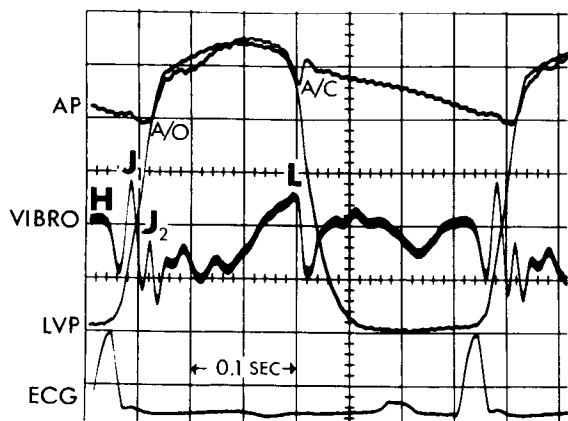


Figure 16

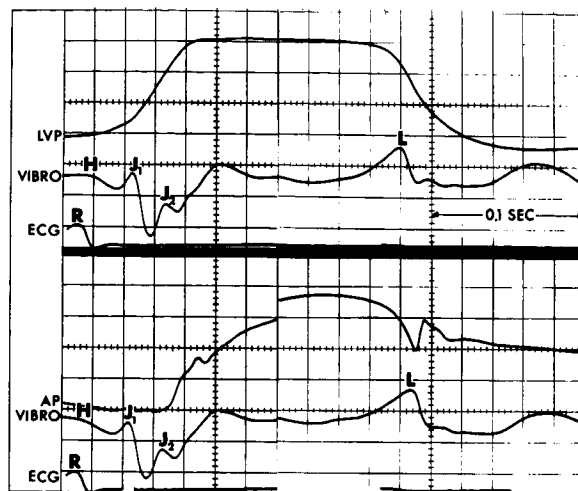


Figure 17

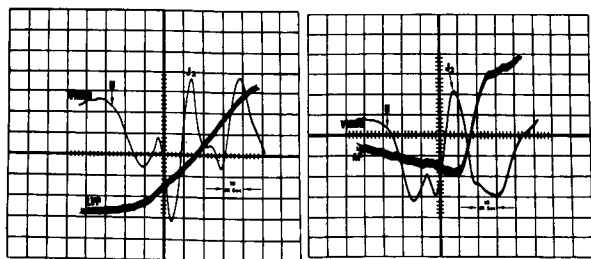


Figure 18

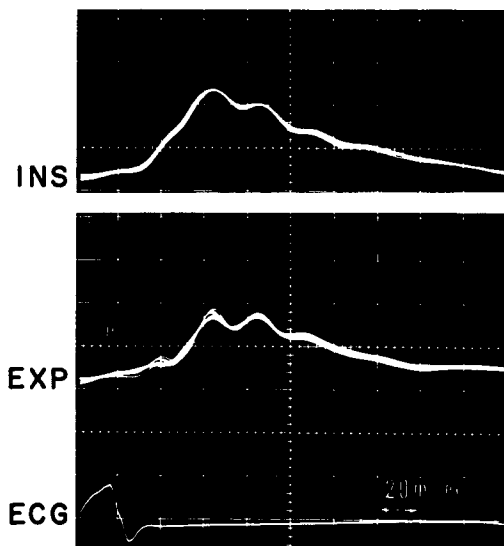


Figure 19

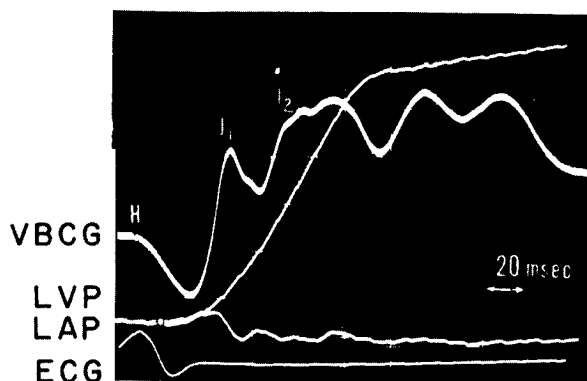


Figure 20  
identify. For these reasons, correlations were not attempted between the auricular events and the VbCG.

The correlations of the pressure phenomena and VbCG waves are listed in the "Table of Left Heart Data" presented on the following page. Each wave and pressure event was measured from the peak of the R wave and listed in terms of elapsed time from this reference point. From these data, the following correlations were made:

- "H" - Occurs with the R peak of the ECG and denotes the initial rise of left intraventricular pressure (range -9 to +4 milliseconds from R peak).

pressure rise, as shown in Figure 20. It was thus impossible to locate precisely the point of mitral closure. Furthermore, the vibrocardiographic deflections at the termination of isometric relaxation and opening of the mitral valve were often of very low amplitude and difficult to

TABLE I  
TABLE OF LEFT HEART DATA  
(Elapsed Time in Milliseconds)

EXPERIMENT		H	LVP	J <sub>1</sub>	RR	J <sub>2</sub>	AO	L <sub>1</sub>	AC
(Samp)									
31.	1	-2	4	34	34			230	232
	2	-2	2	33	34			242	244
	3	-2	0	36	33			247	249
	4	-1	3	29	27			237	239
	5					48	47	251	253
	6					49	47	338	336
34.	1	0	-2	36	38			188	190
	2	3	6	34	36	54	56	186	186
	3	4	2	35	38				
	4	2	2	35	-				
	9	-2	0	35	30	58	58		
	10	0	5	34	30				
	11	-2	2	35	32				
35.	1	-8	0	18	16				
	2	10	2	20	16				
	4	8	2	18	14				
	5	-4	1	18	12				
	6					62	64		
36.	1	6	4	42	40			278	278
	2	11	7	43	-			282	282
	3					86	86		
37.	3	-2	7	38	38	74	74		
	4					73	73		
	5	0	5	34	31				
	6	-2	4	32	-				
	8	0	6	36	-				
	9	0	8	26	28	72	78	292	294
38.	2	4	6	26	25			290	290
	3					66	62		
	5	0	7	26	30				
39.	1	0	0	20	20			214	212
	2	0	0	21	18	52	52	210	208
	3	0	0	20	20			228	226
	4					54	54	224	224
	6					54	54	233	233
	7	0	0	20	18			218	216
	8					52	52		
40.	1	0	5	25	24			254	252
	2	-1	2	31	-			250	248
	3	2	2	32	27	64	60	234	232
	4	0	0	25	25	64	66	204	206
	5					64	66	242	240
	6					66	66		
	7					67	66		
41.	1	0	0	29	29	55	57		
	2					53	53		
	3	0	4	28	-				
	4	0	2	28	26	52	52		
	5	0	0	23	20				
42.	1	0	2	16	18			181	181
43.	1			18	18			166	166
	2	4	2	18	17			152	154
	4					38	40		
	5	2	2	18	16				
44.	1	4	11	34	27				
	2					62	58	298	297
	4					60	58	321	319
45.	1	4	0	22	16				
	2	0	2	29	30				
	4					66	64		
47.	1	6	9	35	33				
	5			34	34	55	52		
	6					58	56		

"J<sub>1</sub>" - Marks the juncture of the period of slow ventricular pressure rise (entrant phase) with rapid pressure rise (isometric pressure gradient), and occurs 18 to 43 milliseconds after the R peak.

"J<sub>2</sub>" - Denotes the onset of aortic pressure rise and occurs 44 to 74 milliseconds after the R peak. However, in one instance the "J<sub>2</sub>" followed the R wave by 38 milliseconds.

"J<sub>3</sub>" - Not correlated with pressure changes but denotes peak of flow.

"L<sub>1</sub>" - Coincides with the aortic incisura (Range: 152 to 338 milliseconds after the R peak).

The correlation of the vibrocardiographic waves and their associated pressure phenomena are graphically illustrated in Figures 21 through 25. In these illustrations, the number of observations are listed on the ordinate and the time in msec (milliseconds) from the event measured on the abscissa. Twenty-seven of 38 "H" wave measurements fell within  $\pm 3$  msec of the onset of left ventricular pressure rise (Figure 21). The peak of the R wave of the ECG showed only slightly higher correlation, 24 of 39

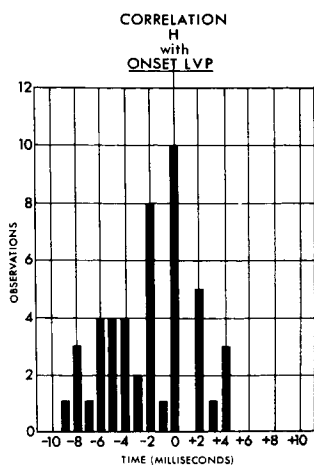


Figure 21

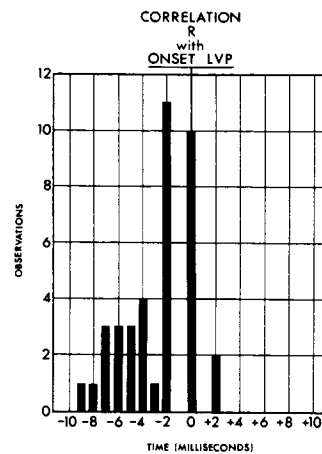


Figure 22

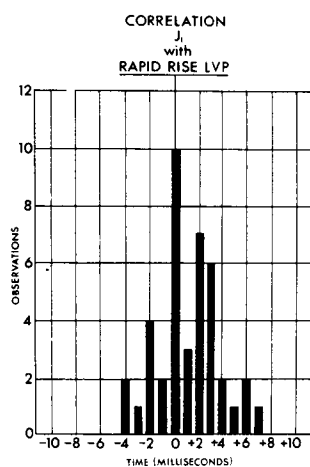


Figure 23

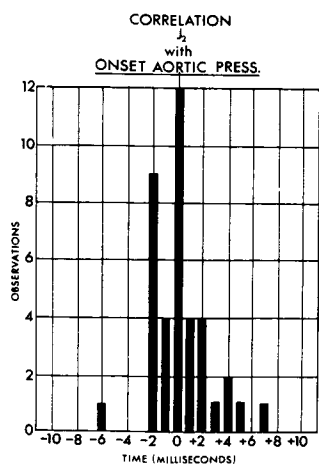


Figure 24

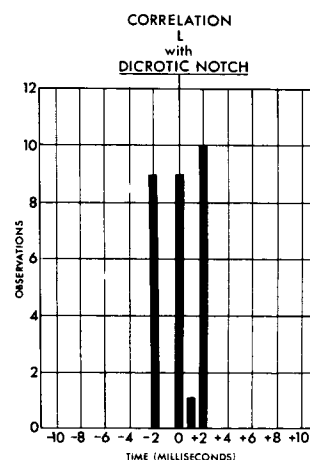


Figure 25

observations occurring within  $\pm 3$  msec (Figure 22). In both "H" and R measurements, the poorest correlations preceded the onset of ventricular pressure rise suggesting that the difficulty in locating the exact point of pressure rise may account for the wider distribution. In 41 observations, the "J<sub>1</sub>" wave correlated within  $\pm 3$  msec in 32 instances (Figure 23). The "J<sub>2</sub>" wave correlated  $\pm 3$  msec with initial aortic pressure rise in 34 of 39 observations (Figure 24) and the "L" wave correlated  $\pm 3$  msec with the aortic incisura in all of the 29 observations (Figure 25).

The time derivatives of the ventricular and AP curves with the VbCG are shown in Figure 26. The derivatives of the

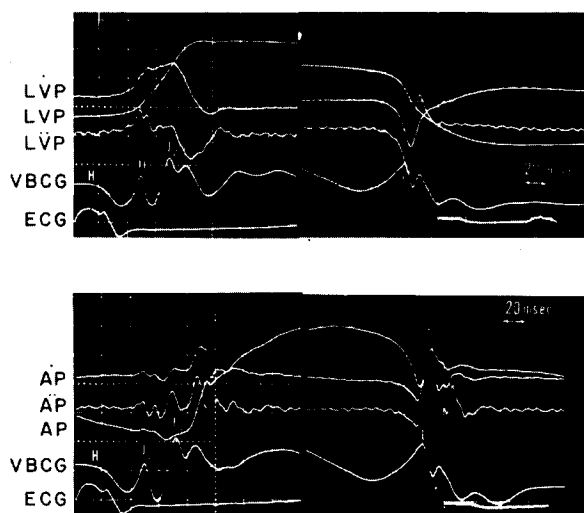


Figure 26

pressure curves facilitate the identification of the initial rise of left ventricular pressure, as this event is accentuated in the time derivatives ( $\dot{LVP}$  and  $\dot{AP}$ ). The correspondence of "H" to this event is evident. Similarly, the relationship of the "J<sub>1</sub>" wave to the juncture of slow and

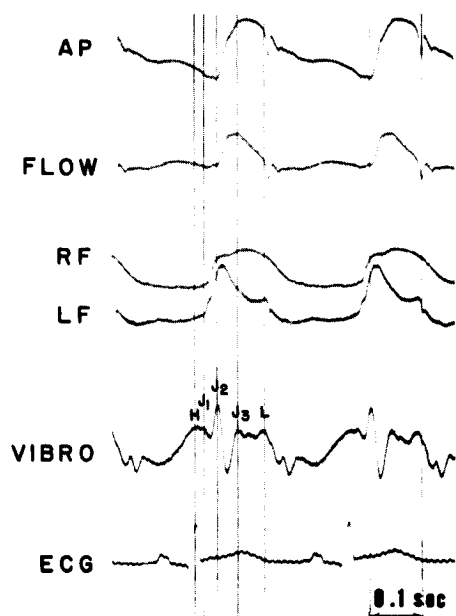
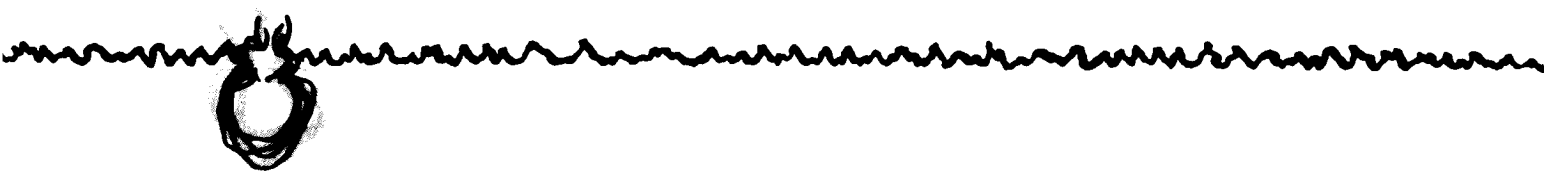


Figure 27

ventricular chamber. The "J<sub>1</sub>" wave correlates with the period of more rapid shortening which is the onset of the period of rapid pressure rise in the left ventricle (as shown earlier in Figure 17). The "J<sub>2</sub>" wave occurs near the end of ventricular shortening in its longitudinal axis and simultaneously with aortic valve opening. The "J<sub>3</sub>" wave, which has not shown a correlation with pressure phenomena, occurs with the peak of aortic flow. The "L" wave corresponds to the initial rapid relaxation (longitudinal) of the left ventricle.

Each of the major waves of the VbCG can be identified on the force tracing, again indicating the relation of these waves to the pressure and contractile events of the left ventricle.



rapid pressure rise is easily noted, as the change in slope of the LVP curve is represented as the rapid rise summit in the second derivative. In 13 of 15 measurements, the " $J_1$ " wave occurred within  $\pm 3$  milliseconds of this event. The remaining two cases were within 4 milliseconds. The " $J_2$ " wave, which was shown to occur with aortic valve opening, also occurs with a change in slope on the ventricular pressure curve, which is evident as the peak in its first derivative. Eleven of 15 " $J_2$ " measurements were within  $\pm 3$  milliseconds of the peak of the ventricular first derivative, two within 4 milliseconds and two within 5 milliseconds. There were no consistent correlations with the vibrocardiographic waves and aortic pressure derivatives. In several instances, there was a wave ( $J_3$ ) which was found to correlate with the peak of the aortic second derivative ( $\ddot{A}P$ ). In the majority of experiments, however, this wave was not identifiable.

Figure 27 is a record of aortic pressure and flow, right and left ventricular force tracings, the vibrocardiogram, and the ECG. The correspondence of the vibrocardiographic deflections to changes in ventricular dimensions is evident. The "H" wave corresponds to the initial shortening of the

### 3.1.1.2 Results - Right Heart

Figures 28, 29 and 30, presented on the following page, illustrate right heart events. In 14 of 30 observations the "H" wave occurred 10 milliseconds after the onset of right ventricular pressure rise, and in 4 of these cases, preceded right ventricular pressure rise by over 20 milliseconds. There were only four observations in which a correlation as close as  $\pm 3$  msec was found. Pulmonic valve opening similarly showed a variable relationship with the "J<sub>2</sub>" wave, with 5 of 7 observations occurring beyond 13 milliseconds of the event, and only one observation occurring within the 3 millisecond limit. The "J<sub>2</sub>" wave, which coincided with aortic valve opening, occurred both prior to, and after, pulmonic opening. Similarly, the "L" wave showed a variable relationship with pulmonic closure. The absence of a relationship between the VbCG and right heart phenomena is further illustrated in Figure 30 by the time derivatives of the pressure curves obtained simultaneously with the VbCG.

Figure 28 illustrates right and left ventricular pressures inscribed simultaneously and shows that the rise of right ventricular pressure follows that of the left and does not correlate with the "H" wave. In the descending limb, the fall of right ventricular pressure precedes that of the left and does not correlate with the "L" wave.

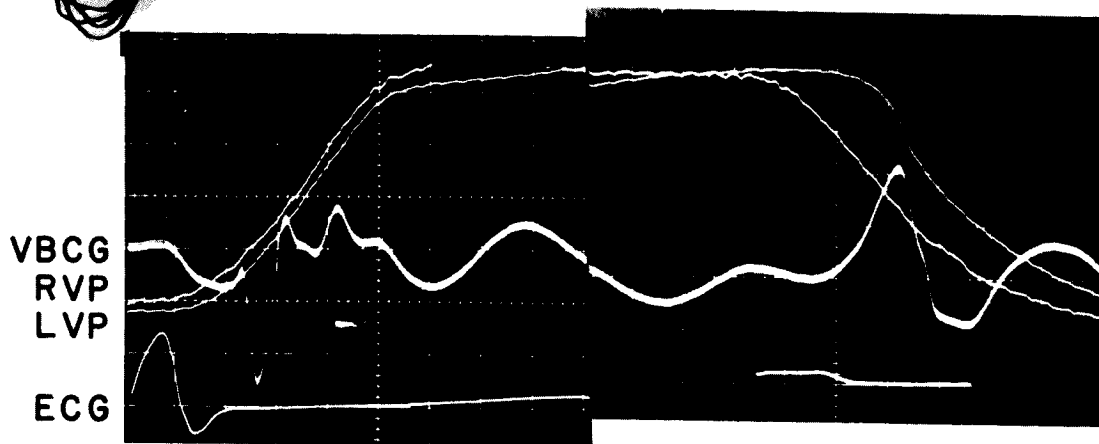


Figure 28

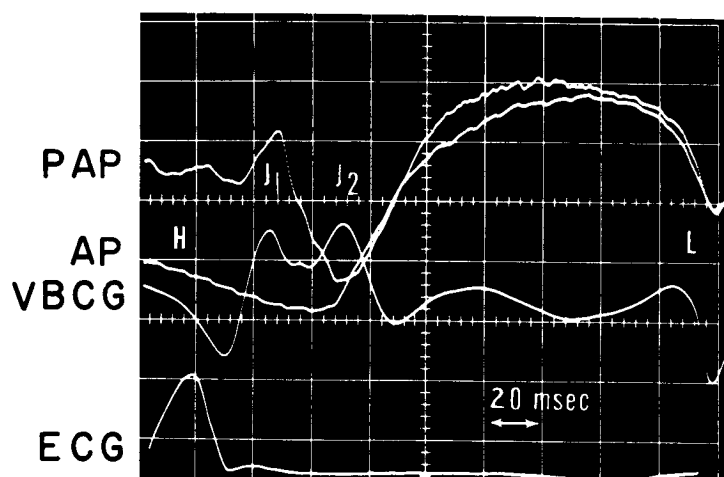


Figure 29

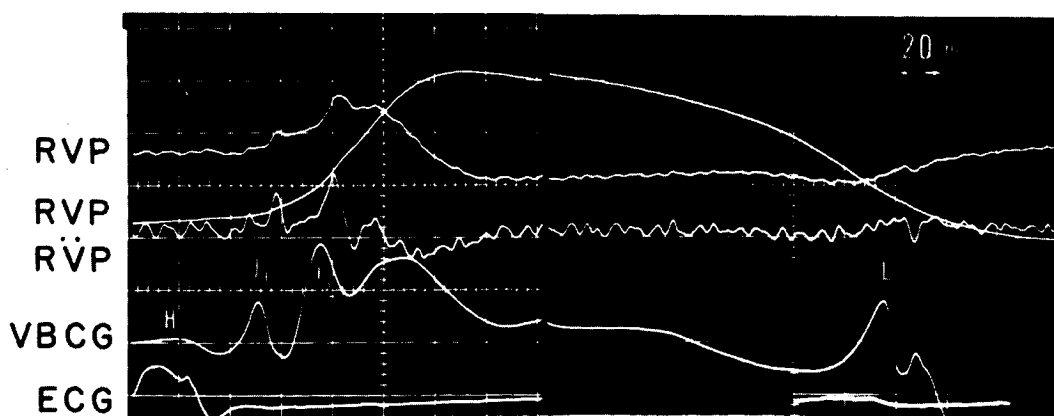


Figure 30

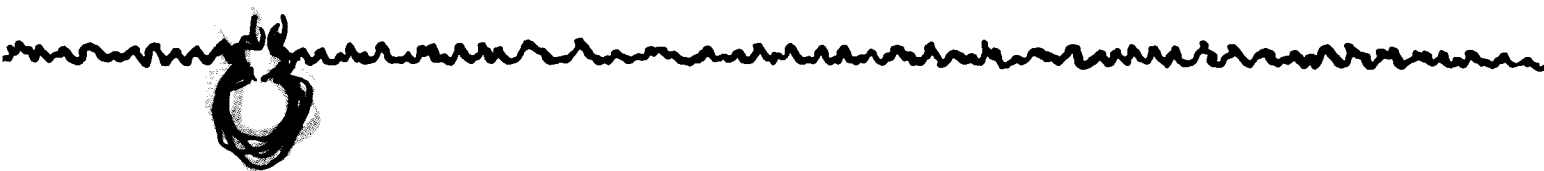
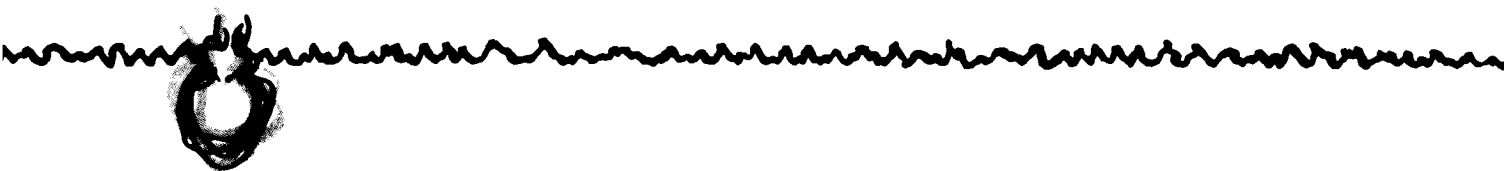


Figure 29 illustrates the simultaneous inscription of pulmonary artery and aortic pressure waves with the VbCG and ECG, and shows that the "J<sub>2</sub>" wave coincides with the rise of AP, but not PAP. In Figure 27, it was noted that the onset of right ventricular shortening occurs approximately 4 milliseconds after the left and does not coincide with any deflection of the vibrocardiogram. Similarly the onset of the period of rapid shortening in the right ventricle occurs later in time than that of the left. Peak force occurs nearly simultaneously in both ventricles and is marked by the "J<sub>2</sub>" wave. The periods of protodiastole and isometric relaxation are denoted by a smooth and gradually diminishing right ventricular force curve, being free of the abrupt changes which occurred in that of the left ventricle and which coincided with the "L" wave.

#### 3.1.1.3 Discussion


The applications of precordial vibration recording techniques for supplementing the electrocardiogram as a heart monitor and as a means of testing heart function have grown rapidly in recent years. All of these techniques — apexcardiography<sup>5</sup>, kinetocardiography<sup>6</sup>, accelerography<sup>11</sup> and vibrocardiography<sup>1</sup> — have demonstrated their usefulness in the identification of cardiac events.



However, their reliability has often been questioned and their accuracy never assessed by instrumentation which would permit millisecond correlations. The use of the transducer tipped catheter which eliminates the time delays of conventional catheter systems, and the oscilloscope which affords extremely high sweep rates, provide the accuracy necessary for precise determinations.

From the study of Figures 21 through 25 (presented earlier), which illustrated pressure events and VbCG wave correlations, it was apparent that very short time periods are involved. The time for depolarization of the ventricular septum in the dog (duration of the "Q" wave) averages 35 msec.<sup>18</sup>, which is three times as long as the poorest correlations in this study.


From these data it is evident that the VbCG deflections are closely related to the pressure phenomena of the left heart. The "H" wave denotes the onset of pressure rise and "J<sub>1</sub>", the juncture of the two phases of isometric contraction, (slow and rapid pressure rise). The "J<sub>2</sub>" wave occurs with the opening of the aortic valve and the "L" wave with its closure. "J<sub>3</sub>" correlates with the peak flow achieved in ejection. The finding that the major VbCG deflections correlate well in time with derivatives of the left ventricular pressure curve and the ventricular



force tracings further demonstrates the close relationship of VbCG waves to the contractile phenomena of the left heart. The absence of such a relationship with right heart pressure curves, or their derivatives and force curves, indicates that the right heart of the dog under normal conditions has very little influence on vibrations as recorded from the left parasternal area.

#### 3.1.1.4 Summary

- \* VbCG<sub>s</sub> were obtained from the left parasternal area in dogs simultaneously with intracardiac pressure curves, the time derivatives of the pressure curves, and with ventricular "force" recordings. By using the technique of polaroid photography from an oscilloscopic screen with sweep speeds up to 1000 mm/sec. transducer tipped catheters measurement accuracies of better than 2 msec. were achieved.
  
- \* The VbCG waves "H", "J<sub>1</sub>", "J<sub>2</sub>" and "L" were found to correlate with: the initial rise of left ventricular pressure; the juncture of the slow and rapid phases of isometric contraction; and opening and closure of the aortic valve, respectively. "J<sub>3</sub>" was found to correlate with the peak flow achieved during ejection.

- 
- \* Pressure time-derivatives and ventricular force recordings from the left heart showed the same time relationships to the VbCG waves.
  - \* No close relationships were found between VbCG waves and right heart pressure phenomena.
  - \* The VbCG can be used as a simple external technique to time the major events of the cardiac cycle with millisecond accuracy.

### 3.1.2 Effects of Hypoxia

The effects of hypoxia have been studied in animals by two methods: The first entailed the use of a spirometer with CO<sub>2</sub> absorbant in which the animal rebreathed, providing a constantly diminishing oxygen supply. In the second method, pre-mixed gases of 10 per cent oxygen were administered through a positive pressure respirator. Vibrocardiograms, aortic and left centricular pressures, and electrocardiograms were recorded throughout these procedures.

The most striking finding has been that the area under the vibrocardiographic curve increases linearly with the duration of hypoxia as exemplified in Figure 31. More definitive studies are now planned using blood flow and cardiac force measurements.

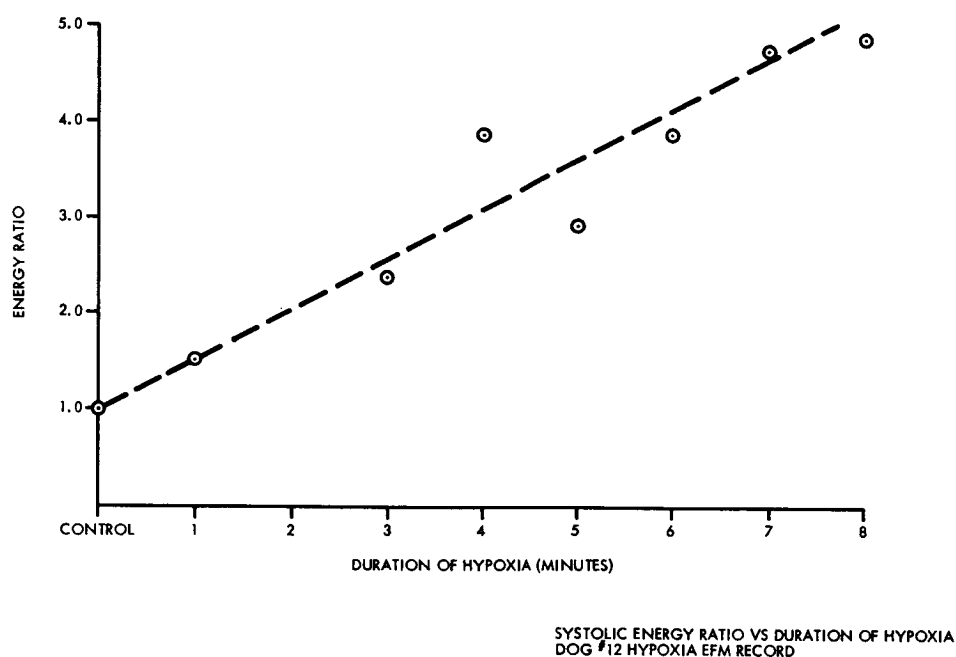
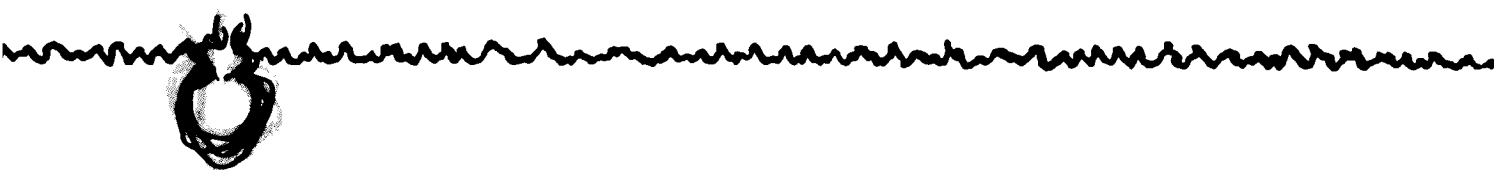


Figure 31

### 3.1.3 Cardiac Injury

Experiments were undertaken to compare the effects of exercise in normal animals and in those which cardiac injury had been produced. The method for the induction of cardiac injury involved the injection of microminiature



plastic spheres into the coronary circulation by a special catheter. This technique has been described in an earlier report. Exercise was induced by electrically stimulating the animals' extremities. Vibrocardiograms, electrocardiograms, intravascular pressures, and in some cases, cardiac output by the dye-dilution technique were obtained. These records were obtained at rest and after exercise in the normal and cardiac injured animals.

The vibrocardiographic and hemodynamic measurements obtained from these studies are shown in Tables II, III, IV and V presented on the following pages. These measurements include:

1. The vibrocardiographic wave intervals corresponding to isometric contraction ( $H-J_2$ ) and ejection ( $J_2-L$ ).
2. Mean arterial pressures which were obtained from a transducer tipped catheter placed in the central aorta. ( $1/3$  pulse pressure plus diastolic pressure).
3. The time-tension index (TTI) which is the product of the mean systolic pressure and the ejection time. This measurement was described by Sarnoff and has shown to be directly related to myocardial oxygen consumption.

# NORMAL REST DATA

TABLE II

<u>EXPERI- MENT</u>	<u>MSP</u>	<u>J<sub>2</sub>-L</u>	<u>TTI</u>	<u>DP-EDP</u>	<u>H-J</u>	<u>V.S.</u>	<u>H-J<sub>2</sub> J<sub>2</sub>-L</u>	<u>RATE</u>	<u>E. Time Sec/Min</u>	<u>MSER</u>
1.	123	0.136	1675	110-0	0.063	1745	464			
2.	103	0.218	2250	90-0	0.074	1220	340	95	20.8	
3.	133	0.162	2160	120-0	0.065	1850	400	152	24.5	340
4.	133	0.128	1700	120-0	0.055	2180	425	160	-20.5	
5.	127	0.131	1665	110-10	0.067	1490	510			
6.	113	0.212	2390	100-0	0.055	1820	260	90	-19.0	
7.	120	0.141	1690	110-6	0.047	2210	330	160	22.5	
8.	130	0.119	1550	120-8	0.046	2440	386	169	20.0	
9.	147	0.195	2760	135-18	0.057	2060	292	122	23.8	333
10.	123	0.183	2250	110-10	0.045	2220	246	112	20.5	235
11.	105	0.146	1533	95-10	0.068	1250	465			
12.	92	0.176	1620	80-10	0.056	1250	318	110	19.4	
13.	97	0.184	1780	90-0	0.045	2000	244	169	31.0	
14.	125	0.144	1800	110-10	0.050	2000	347	115	16.5	
15.	113	0.138	1560	100-0	0.066	1520	478			
16.	147	0.152	2240	130-10	0.050	2400	328	130	-19.8	
17.	142	0.177	2520	130-8	0.049	2490	277	112	19.8	
18.	127	0.176	2240	110-0	0.037	2700	210	110	18.2	
19.	123	0.117	1440	110-15	0.050	1900	428	154	18.0	214
20.	138	0.132	1820	120-0	0.067	1790	510			
21.	170	0.129	2200	160-18	0.065	2180	500	182	23.5	
22.	133	0.150	2000	120-0	0.051	2350	340	127	19.0	
23.	138	0.186	2570	120-0	0.050	2400	270	113	21.0	

## NORMAL - POST EXERCISE PER CENT CHANGE

TABLE III

<u>NO.</u>	<u>MSP</u>	<u>J<sub>2</sub>-L</u>	<u>TTI</u>	<u>DP-EDP</u>	<u>H-J</u>	<u>V<sub>s</sub></u>	<u>H-J<sub>2</sub> J<sub>2</sub>-L</u>	<u>RATE</u>	<u>E. Time Sec/Min</u>	<u>MSER</u>
3	+11	-32	-23	+ 8	-41	+92	-14	+36	- 6	+60
4	+11	- 4	+ 7	+ 8	- 2	+17	- 2	+ 6	+ 2	-
7	+17	- 2	+20	+12	+28	-12	+33	+ 4	+ 2	-
8	+ 5	- 3	- 8	- 6	0	- 7	- 3	+ 3	+ 6	-
9	- 5	- 4	- 5	- 9	-35	+42	-32	- 4	- 8	- 1
10	+14	- 8	+ 4	+10	-13	+27	- 6	0	- 3	+22
12.	+15	- 8	+ 7	+21	- 7	+31	+ 1	+17	+ 8	-
16.	0	0	0	0	+ 4	- 4	+ 4	+12	+13	-
17.	-11	-12	-21	-18	- 2	-16	+11	-13	-23	-
18.	+ 9	- 7	- 2	+ 9	+22	- 1	+31	+ 6	- 4	-
19.	+12	-10	+ 1	+11	+16	+ 4	+29	+ 7	- 3	+68
23.	+13	+ 1	+14	+17	- 2	+19	- 3	+ 3	+ 3	

POST INFARCTION  
PER CENT CHANGE

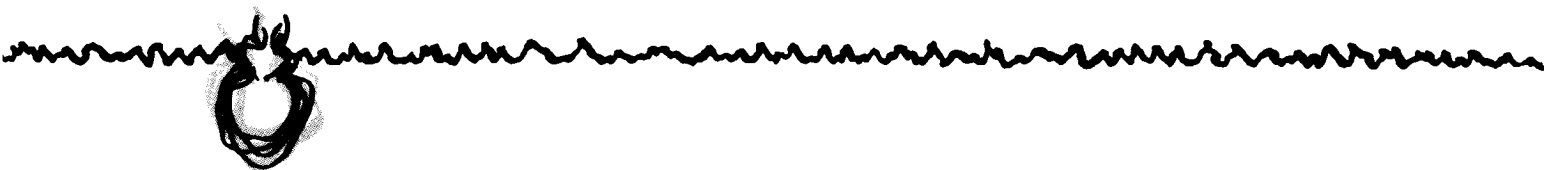
TABLE IV

<u>EXPERI- MENT</u>	<u>MSP</u>	<u>J<sub>2</sub>-L</u>	<u>TTI</u>	<u>DP-EDP</u>	<u>H-J<sub>2</sub></u>	<u>V.S.</u>	<u>H-J<sub>2</sub> J<sub>2</sub>-L</u>	<u>RATE</u>	<u>E. Time Sec/Min</u>	<u>MSER</u>
7 Apr.	-11	-14	-23	-13	+50	-35	+74	-15	-23	
18 Apr.	-20	- 8	+ 3	+ 9	+42	-20	+53	- 9	-17	
27 Apr.	-14	-12	-25	-21	-25	+ 5	-15	+23	+ 8	
27 Apr.	-20	- 9	-28	-31	- 5	-27	+ 6	+11	+ 1	
1 Aug.	+ 5	-11	- 7	+ 9	+50	-26	+70	+ 5	- 8	
10 Aug.	- 2	- 5	- 7	-11	-27	+23	-24	+16	+11	+30
15 Aug.	-33	- 5	-37	-23	+22	-37	+83	+25	- 9	-64
23 Aug.	-17	-17	-31	-25	-15	-11	+ 2	0	-17	-35
26 Oct.	-31	- 3	-33	-29	+15	-38	+19	- 7	-10	-16

POST INFARCTION - EXERCISE  
PER CENT CHANGE

TABLE V

<u>EXPERI- MENT</u>	<u>MSP</u>	<u>J<sub>2</sub>-L</u>	<u>TTI</u>	<u>DP-EDP</u>	<u>H-J<sub>2</sub></u>	<u>V.S.</u>	<u>H-J<sub>2</sub> J<sub>2</sub>-L</u>	<u>RATE</u>	<u>E. Time Sec/Min</u>	<u>MSER</u>
7 Apr.	+19	+12	+33	0	-47	+67	-47	+24	+39	
18 Apr.	+ 2	+ 4	+ 7	- 7	-30	+19	-33	+ 6	+11	
27 Apr.	- 3	+ 4	+ 1	-11	0	-10	- 3	- 4	0	
27 Apr.	- 4	- 2	- 6	- 4	-13	+11	-11	- 6	- 9	
1 Aug.	+13	- 6	+ 6	+ 8	-17	+30	-13	+11	+ 4	
10 Aug.	0	0	0	+ 6	+12	- 6	+13	- 2	- 2	-66
15 Aug.	+22	- 3	+20	+11	0	+11	+ 3	+ 3	0	+77
23 Aug.	+ 3	- 4	- 1	0	- 9	+10	- 5	+ 5	+ 1	+ 7
26 Oct.	+29	0	+29	+38	-20	+69	-20	+15	+15	-79

- 
4. The ventricular slope, which is the quotient of the isometric pressure gradient (DP-EDP) and the isometric contraction time ( $H-J_2$ ), and yields a measurement of the rate of development of pressure during isometric contraction.
  5. The isometric contraction-ejection ratio;  $(H-J_2) - (J_2-L)$ .
  6. The ejection time, expressed in seconds of ejection per minute.
  7. The mean systolic ejection rate (MSER) which is the stroke volume divided by ejection time and indicates the rate at which ejection is occurring.

The data obtained from the resting animal is shown in Table II and per cent change of these parameters, in the normal animal after exercise, is shown in Table III. The mean systolic pressures showed an average increase of eight (8) per cent and the heart rate had an average increase of seven (7) per cent. The TTI showed a more variable response; four (4) experiments showing a decrease; two (2), no change; and six (6), increasing. The ventricular slope, however, increased in seven (7) of the 12 experiments. The "H-J" intervals and also the " $H-J_2/J_2-L$ " ratios showed a similarly mixed response. In the four (4) experiments in which cardiac outputs were obtained, the mean systolic ejection rate increased significantly in three (3) and fell slightly in one (1).

After the induction of cardiac injury, Table IV, the resting mean systolic pressures dropped an average of 12 per cent, the " $J_2$ -L" interval shortened nine (9) per cent, and thus the TTI diminished 21 per cent. In five (5) experiments, the " $H-J_2$ " interval was significantly increased and the " $H-J_2/J_2-L$ " ratios similarly were increased in five (5) of the nine (9) studies. The heart rates showed variable changes, five (5) increasing and three (3) decreasing and the ejection times, in seconds per minute, also showed the same variability. The ventricular slope was diminished in seven (7) experiments and the mean systolic ejection rate diminished in three (3), and elevated in one (1). While the changes in most of these parameters were somewhat variable, definite trends can be seen in the TTI, the ventricular slope, and the " $H-J_2/J_2-L$ " ratio.

The exercise data after myocardial infarction are presented in Table V. The mean systolic pressure, the " $J_2$ -L" interval and the TTI all demonstrated variable changes after exercise. The ventricular slope was increased in seven (7) experiments, whereas the " $H-J_2/J_2-L$ " ratio was diminished in seven (7) experiments. The MSER was diminished in two (2) and increased in two (2).

Although there was great variability in the change of the parameters after exercise, it is interesting to note that the vibrocardiographic " $H-J_2/J_2-L$ " ratio showed a consistent decrease in the cardiac injured animal. The TTI and ventricular slope changes were similar to those noted in the normal animal and did not serve to differentiate the normal from the cardiac injured response to exercise.

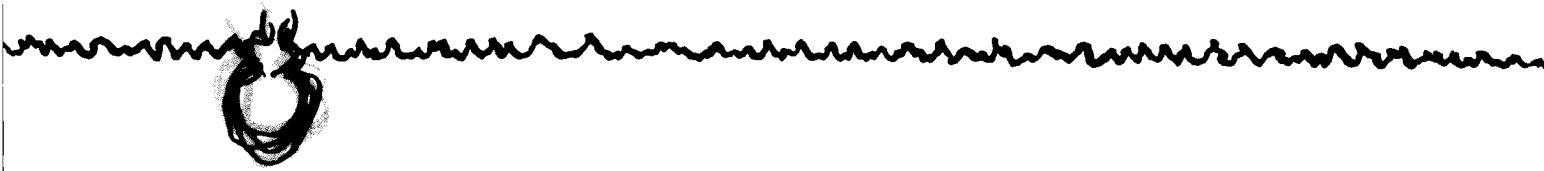
The variability in some of these parameters may be attributed to the fact that these were anesthetized animals with varying degrees of exercise. Further experimentation of this type is discussed in the "Proposed Research" section of this document.

### 3.1.4 Preliminary Animal Experiments

Presented below is a brief report on various preliminary experiments that have been conducted but were not reflected in our original research proposal to NASA. The need for conducting each of these preliminary experiments is described in each case.

#### 3.1.4.1 Strain Gauge Arch Experiments

The purpose of these experiments was to determine whether a measurement of cardiac force could be obtained from the VbCG. In human experiments, discussed later in Section 3.2, the ballistocardiogram has been utilized as an indicator of cardiac force and correlated with the VbCG. A more direct approach to this problem can be obtained in the animal subject by use of a strain gauge sutured directly to the myocardium, in which case cardiac force can be recorded directly and correlated with the VbCG. Several pilot studies of this type have been performed by our research staff. The device for measuring cardiac force was a



Waltham-Brodie strain gauge arch.\* Utilizing a dog subject, the instrument was sutured to the left ventricular wall near the apex and the leads passed through the right chest wall for external recording.

After a few days recovery period, recordings were obtained of cardiac force, VbCG's and ECG's at rest and during exercise. A typical record of these types of data was shown earlier in Figure 27. The correspondence of the vibrocardiographic waves to the left ventricular dimension changes, particularly those of ventricular systole, is evident. Note, in Figure 27, that the major vibrocardiographic waves are represented on the strain gauge arch tracing (RF and LF). The method of analysis of the VbCG in these studies involves measurement of the area under the "squared" vibrocardiographic curve during the phase of ventricular systole. These measurements were then compared to the cardiac force data as obtained from the strain gauge arch in resting and exercise records. Preliminary data indicates a close relationship between the energy content of the VbCG (area under the "squared" curve) and cardiac contractile force.

---

\*Instructions and general information regarding use of the strain gage arch in measurement of heart force changes, March, 1961.

#### 3.1.4.2 Flow Experiments

These studies were performed to determine if an indication of stroke volume can be obtained from the VbCG. The method of flow determination in these studies was that of Jones, et al.\* which requires only an aortic root pressure curve for its operation. The simplicity of this technique, as compared to other flow measuring devices which generally require thoracotomy for implantation, has been found extremely advantageous in our studies.

These experiments consisted of passing a pressure sensing catheter (transducer tipped Statham) to the root of the

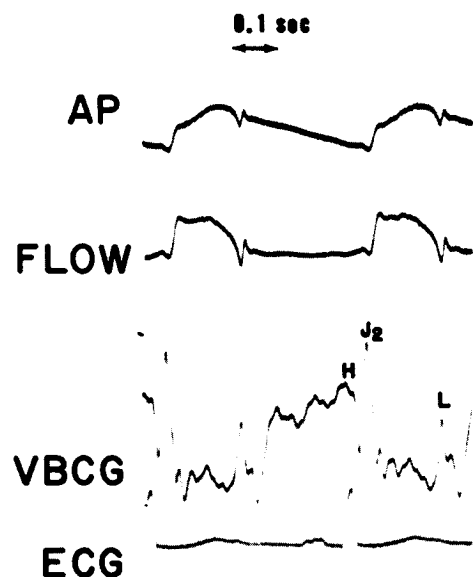


Figure 32

aorta and coupling the output of this transducer to the "pressure-flow converter".

The output of the device, along with the VbCG, aortic pressure and ECG were recorded (Figure 32) at rest during exercise and after administration of nor-epinephrine. In this manner, stroke volume and cardiac output were determined throughout the stress procedures.

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\*Jones, W. B.; Hefner, L. L.; Bancroft, W. H. Jr, and Klip, W. Velocity of blood flow and stroke volume obtained from the pressure pulse. J. of Clin. Investigation, 38:2087, Nov. 1959.

Of interest in these records was the finding that the " $J_3$ " wave, which has not correlated with left ventricular pressure phenomena correlates well with peak aortic flow (rapid ejection).

The VbCG's were analyzed by measuring the area under the ejection portion of the curve ( $J_2$ -L) and comparing these measurements to the area under the flow curve, which represents total flow for this time period (stroke-volume). The computer-

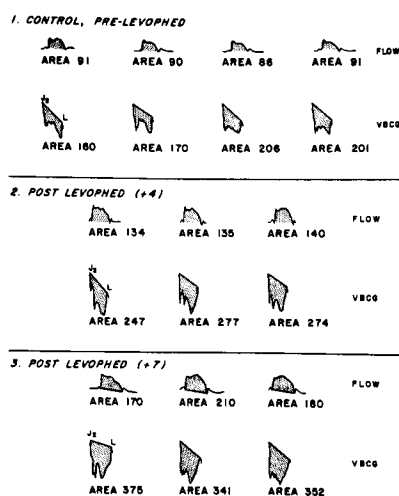


Figure 32-A

processed data from these measurements, before and after administration of nor-epinephrine, are presented in Figure 32-A. It will be noted that there is a good correlation between the vibrocardiographic " $J_2$ -L" area (ejection) and stroke volume in both the exercise records and during the administration of nor-epinephrine.

### 3.1.4.3 Thoracic Transfer of Cardiac Energy

The results of our preliminary experiments in this area have been published in the "Proceedings of the San Diego Symposium for Biomedical Engineering - 1963". A reprint of this material is presented on the following pages.

REPRINT OF THE  
PROCEEDINGS  
*of the*  
SAN DIEGO SYMPOSIUM  
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ENGINEERING  
1963

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THORACIC TRANSFER OF CARDIAC ENERGY

By  
C.M. Agress, M.D., S. Wegner, and K. Schroyer

Cedars of Lebanon Hospital  
Los Angeles, California

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# THORACIC TRANSFER OF CARDIAC ENERGY

by

Clarence M. Agress, M.D., Stanley Wegner and Kenneth Schroyer

## Introduction

Since the original work by Marey in 1865, extensive study has been devoted to the refinement of techniques for recording the vibrational energy of the heart. Despite this concerted effort, the origin and significance of vibration tracings obtained from the precordium are still disputed. The present study was performed to determine the function of the lung-thorax system in the transfer of cardiac vibrational energy. An attempt was made to simulate the transfer characteristics of the lung-thorax system by electronic circuitry.

The requisites for this investigation include an understanding of the relationships between the inputs to the system, which represent the forces generated during cardiac contraction and relaxation, and the output of the system which represents the vibrations of the chest wall as a result of cardiac contractile energy.

Previous studies in this laboratory have shown that precordial vibrations have precise time relationships to the events of the left heart rather than the right heart.<sup>(1,2)</sup> indicating that the left ventricle is the dominating chamber in the production of cardiac vibrational energy. In this preliminary series of experiments, therefore, the pressure generated by the left ventricle was utilized as the input to the simulated lung-thorax system.

## Methods

Dogs, ranging in weight from 35 to 50 pounds and anesthetized with intravenous pentobarbital were used in this study. The left heart pressure measurements were obtained by passing a fluid-filled double lumen catheter through the left carotid artery to the aorta and left ventricle. The pressure transducers were Statham P23Gb strain gauges. In later experiments, a Statham SF1 catheter with the transducer located in its tip was utilized for this measurement.

Precordial vibrations were obtained by a capacitance transducer placed over the fourth left interspace. This transducer, manufactured by Ling-Temco-Vought, has a flat response from 5 to 500 c.p.s.\* and a dynamic range of 74 decibels.\* In designing the circuitry for the lung-thorax simulator, advantage was taken of a previous

\* Manufacturers specifications.

observation that the vibrocardiogram resembled a first time-derivative of left ventricular pressure.<sup>(3)</sup> Initially, therefore, the circuit consisted of a simple R-C differentiating network. In later experiments, a second differentiating network and a resistive summing circuit were added for the addition of aortic pressure derivatives. Finally, an 8 C.P.S. L-C resonator was included to simulate the natural frequency of the chest wall.<sup>(4)</sup> A block diagram of this system is shown in Figure 1.

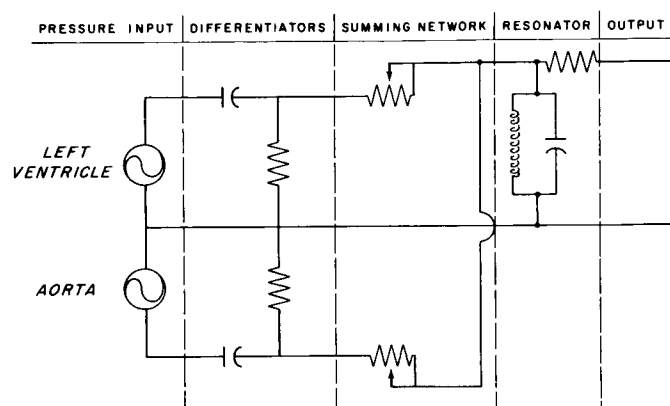


Figure 1

The outputs of the lung-thorax simulator, in addition to the simultaneously obtained vibrocardiogram and left heart pressure curves were displayed on an Electronics for Medicine photographic recorder.

## Results

Illustrated in Figure 2 is the simultaneously obtained vibrocardiogram, left ventricular pressure, and first time derivative of left ventricular pressure. The similarity of the vibrocardiogram and the pressure derivative wave forms is apparent. The major difference between the two curves occurs in the area corresponding to the descending limb of the pressure curve. It is probable that "whipping" of the catheter during this phase of the cardiac cycle produced high frequency artefacts which are further amplified by differentiation. Figure 3 represents the vibrocardiogram, left ventricular pressure and first time derivative of ventricular summated with the first derivative of aortic pressure. It is evident that a closer reproduction of the vibrocardiogram is obtained by the addition of the aortic component. At the time of writing this report, studies with

the 8 c.p.s. resonator which would simulate the natural frequency of the chest wall had just been initiated. From inspection of preliminary data, however, it seems that the addition of this circuitry to the lung-thorax simulator results in a closer approximation of the transfer characteristics of the chest wall.

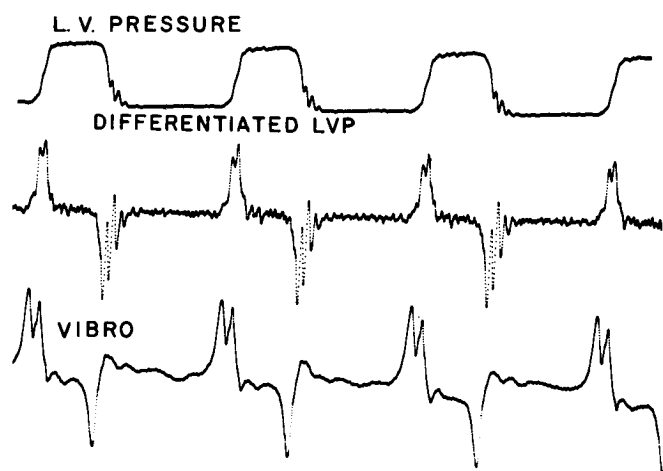


Figure 2

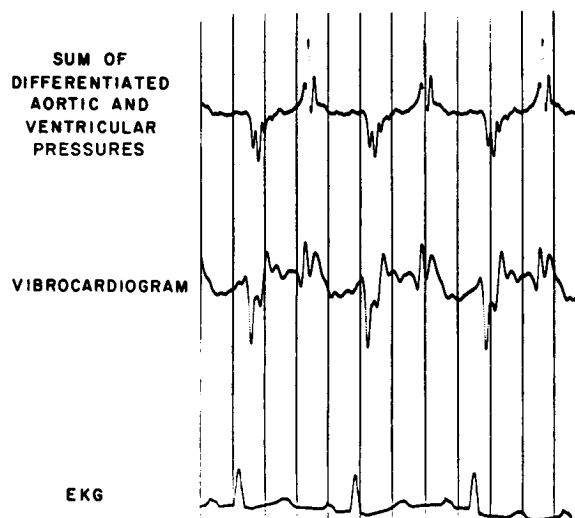


Figure 3

### Discussion

The experiments performed in this study illustrate the probable mechanism for the transfer of cardiac energy to the chest wall. From the data obtained, it is evident that the predominant factor in the production of precordial vibrations in dogs is the activity of the left heart.

Since cardiac energy is dissipated through blood flow and is manifested by pressure rises in the major vessels, it seemed obvious that this pressure change would

be represented in the vibrocardiogram. Therefore, the aortic pressure was added to the simulator. Since the natural frequency of the chest wall should also modify the energy transfer, a resonator was later included.

The action of the lung-thorax system can then be described as having the properties of a mechanical differentiating network where the movement of the chest wall is proportional to the rate of change of pressure in the left ventricle and aorta.

The implications of such a concept also suggest that a determination of intracardiac pressure may be obtained by applying the inverse of the transfer-function (integration) to the vibrocardiogram. Since the boundary values of the vibration tracing with respect to intracardiac pressure are unknown, only a relative pressure measurement may be obtained (Figure 4).

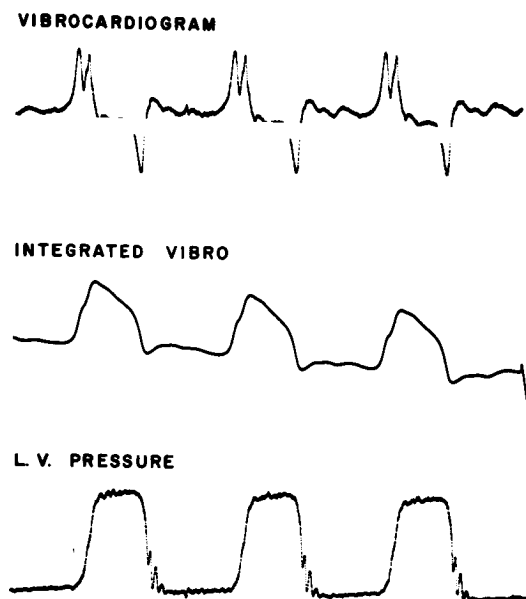


Figure 4

### Summary

Experiments were undertaken to relate intracardiac energy, as obtained from pressure transducers within the left ventricle and aorta, to vibration tracings obtained from the chest surface (vibrocardiogram). The characteristics of the wave forms obtained from the heart and the chest wall have been compared.

It is hypothesized that the action of the lung-thorax system can be described as having the properties of a differentiating network. Thus, the movement of the chest wall is primarily proportional to the rate of change of pressure in the dominant heart chambers.

Integration of the vibrocardiogram can be utilized to obtain a qualitative indication of the pressure generated within the heart.

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#### Biographies

Clarence M. Agress, M.D., received his A.B. at Harvard in 1933 and his M.D. at the University of Texas in 1937. He served as Intern at the Los Angeles County Hospital from 1937 to 1939 followed by a period of three years at the same location as Resident M.D. From 1941

to 1942, he was also a Medical Instructor at the University of Southern California. Then, for a period of four years, Dr. Agress served as Major in the U.S. Army. Following his discharge he was Assistant Clinical Professor at University of Southern California for a period of four years. From 1953 to 1954, he was Chief of Medicine at Los Angeles County Harbor General Hospital.

Since 1955 he has served as Associate Clinical Professor at University of California, Los Angeles. Also, for the past several years, he has served as Cardiology Consultant to the Veterans Administration Hospital in Los Angeles. At Cedars of Lebanon Hospital, since 1960, he has served as Chief of Cardiology.

Stanley Wegner, Research Physiologist, attended the University of California at Los Angeles, Cardiovascular Research Laboratory, University of California Department of Medicine, from 1959 to 1961. He is associated with the Cardiovascular Research Laboratory at the Cedars of Lebanon Hospital since 1961 to the present.

Kenneth Schroyer received his B.A. in Mathematics from Pennsylvania State University in 1957. While doing graduate work in Electrical Engineering from 1957 to 1959, he was employed as a Research Assistant in Physics for the X-Ray and Crystal Analysis Laboratory at Penn State. During the next 18 months he served as a Western Electric Field Engineer on the Nike Missile Program. Subsequent to this period, Mr. Schroyer was employed by the Bendix Corporation as a System Engineer on the Pacific Missile Range.

In September of 1962 he joined Telecomputing Services, Inc., where he presently holds the position of Systems Engineer. During this period he has also served as a Consultant to Dr. Agress for Laboratory Research and System Design.

### 3.2 Human Studies

The following subsections present the results of our human studies. The relationship of the vibrocardiogram to precordial position is first discussed. Then, our findings are presented concerning the correlation of the VbCG and ECG with the functional status of exercised normal males and those with ischemic heart disease. This is followed by discussions concerning the correlation of maximum oxygen consumption (in athletes) with the vibrocardiogram, human hypoxia studies and energy content studies.

#### 3.2.1 Relationship of the Vibrocardiogram with Precordial Position

The purpose of this study was to determine the variations in timing and wave form of vibrocardiograms recorded from multiple positions on the precordium. Moreover, this study was intended to provide further insight into the transfer characteristics of the lung thorax system in the transmission of heart energy to the precordium.

Eleven male athletes were used in this study. Their ages ranged from 17 to 37 years (average 28). A supine chest X-ray (6 foot) was taken in quiet expiration to determine the cardiac position and its projection on the chest wall.

All the subjects were studies in the supine position and the precordium marked into 63 transducer locations from the right sternal border to the left axillary line encompassing the second through the fifth interspaces. These positions are illustrated in Figures 33 and 34 below.



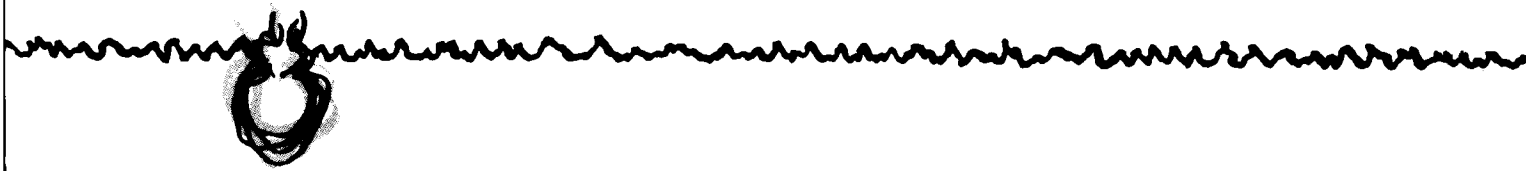
Figure 33

*POSITION NUMBERS OF MICROPHONE ON PRECORDIUM*

	I	S	II		III		IV		V
2 - I. S.	1	8	15	22	29	36	43	50	57
	2	9	16	23	30	37	44	51	58
3 - I. S.	3	10	17	24	31	38	45	52	59
	4	11	18	25	32	39	46	53	60
4 - I. S.	5	12	19	26	33	40	47	54	61
	6	13	20	27	34	41	48	55	62
5 - I. S.	7	14	21	28	35	42	49	56	63

Figure 34

The point of maximal impulse (apex) was located by palpation and auscultation. The microphone (LTV-2) was then attached to the subject by means of an elastic strap and recordings obtained from the 63 positions at the end of expiration.



The recording instrument utilized was the Tektronix oscilloscope with polaroid camera attachment. The R peak of the ECG was employed to trigger the sweep of the oscilloscope, so that the same systolic deflections were displayed on each sweep. Photographs were obtained at 500 mm/sec., so that the vibrocardiographic data could be measured to within 2 msec.

The vibrocardiographic waves "H", "J<sub>1</sub>", and "J<sub>2</sub>" were measured from the data obtained at all 63 microphone positions in relation to the peak of the R wave on a simultaneously recorded electrocardiogram (II). The records obtained from two subjects are shown in Figures 35 and 36. Actual data measurements are presented in Tables VI, VII and VIII. These Tables and Figures are presented on the following pages. The time relationships of the vibrocardiographic waves to the R wave of the ECG varied according to the area where the microphone was placed. In order to assess these timing alterations, an actual size chart of the precordium was drawn for each subject. The precordial areas in which the vibrocardiographic waves made their earliest appearance (shortest R-VbCG time) were marked and considered as zero points. Contour lines were then drawn connecting areas in which progressively greater R-VbCG time intervals were encountered. Plots of R-H, R-J, and R-J<sub>2</sub> contours on one subject (Knox) are presented in Figures 37, 38 and 39 respectively.

KNOX, 17 Yr Old Male

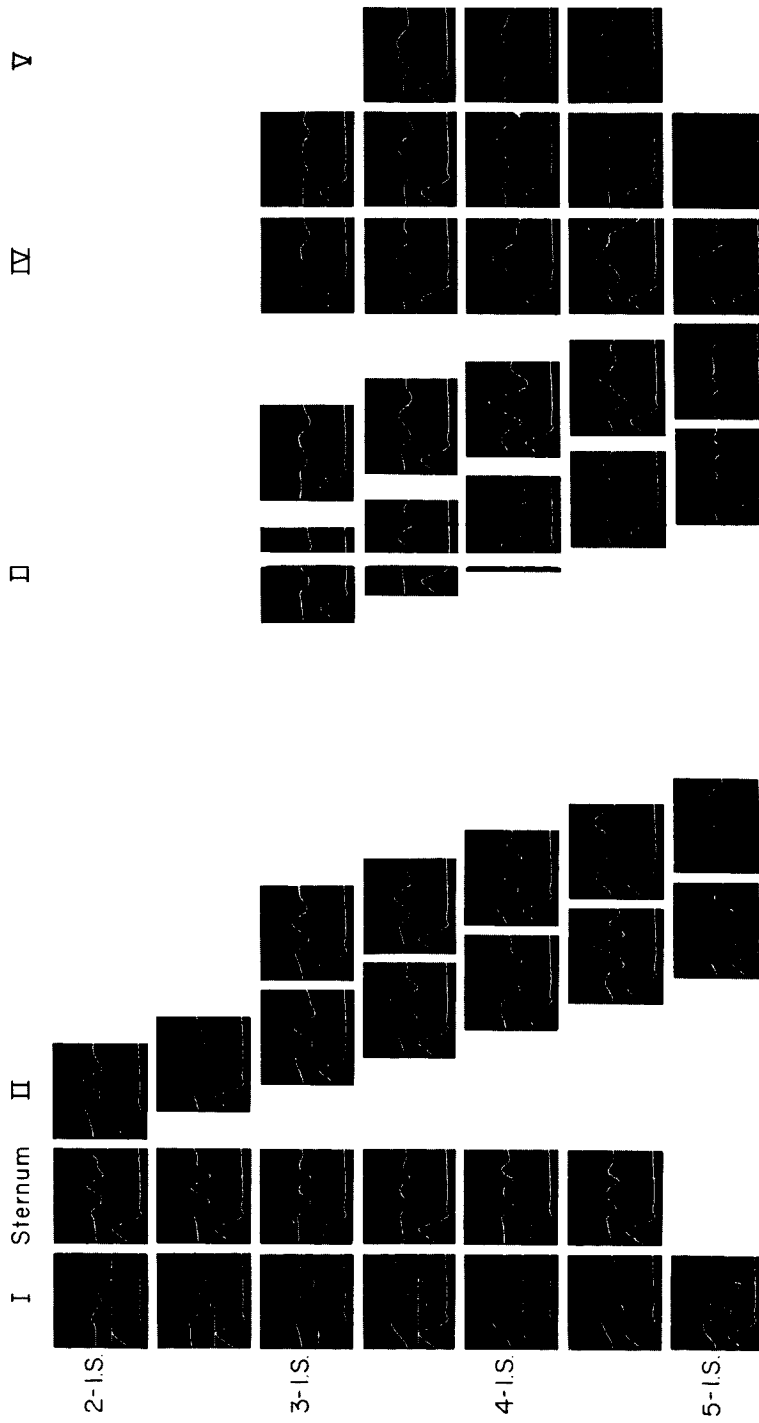


Figure 35

PRANKE, 27 Yr. Old MALE

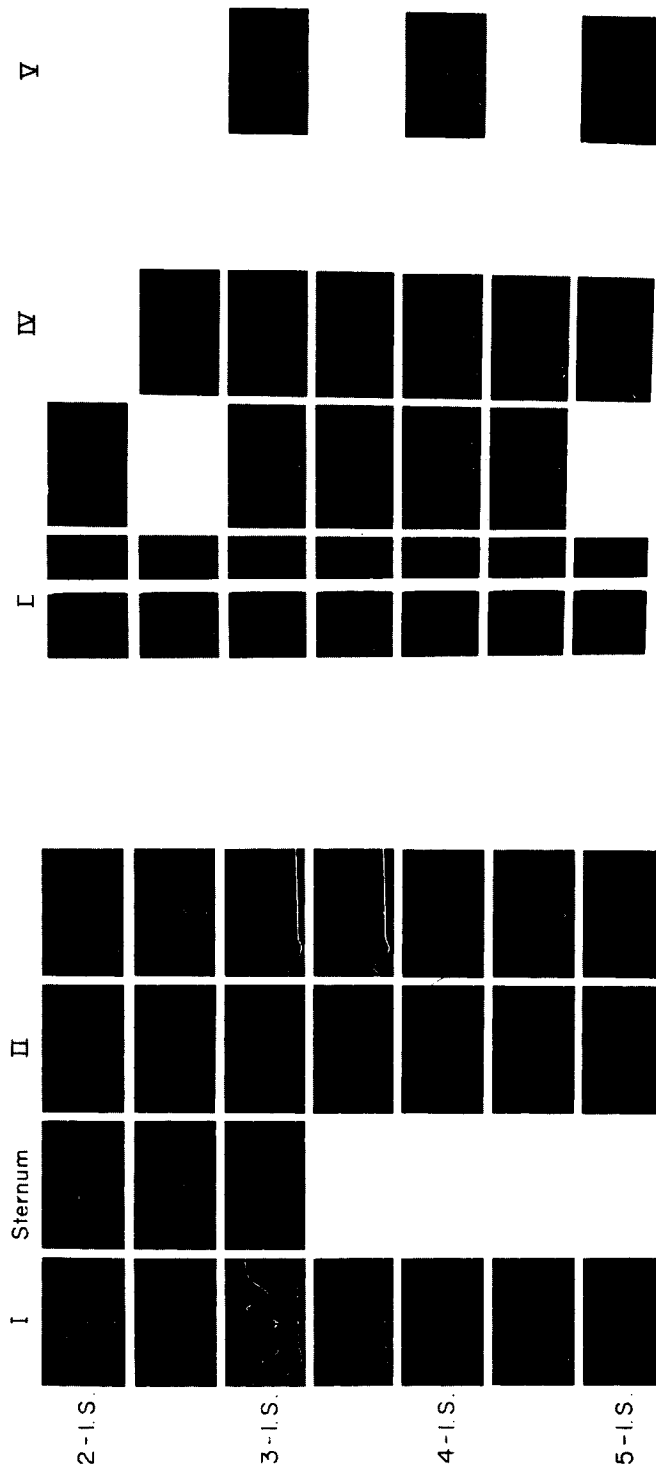


Figure 36

TABLE VI

R-H INTERVALS (MILLISECONDS)

Microphone Position Number	Case No.										
	1	2	3	4	5	6	7	8	9	10	11
1	u	u	-3	--	--	--	--	--	--	u	--
2	u	u	-3	--	--	--	--	--	--	u	--
3	u	u	-2	--	--	--	--	--	--	u	--
4	u	u	-1	--	--	--	--	--	u	u	--
5	u	u	-2	--	--	--	--	--	u	u	--
6	u	u	1	--	--	--	--	--	u	u	--
7	u	u	1	--	--	--	--	--	u	u	--
8	u	u	u	--	--	u	--	--	u	u	--
9	u	u	-1	--	--	--	--	--	u	u	--
10	u	u	u	--	--	u	--	--	u	u	--
11	u	u	--	--	--	u	--	--	u	u	--
12	u	u	--	--	--	u	--	u	u	u	--
13	u	5	--	--	--	--	--	u	u	u	--
14	--	4	--	--	--	--	--	u	u	u	--
15	u	u	5	--	--	u	--	--	u	u	--
16	u	u	u	--	--	u	--	--	u	u	--
17	u	7	3	u	u	u	u	--	u	u	u
18	u	5	-1	u	u	u	u	u	u	u	u
19	5	1	0	u	u	u	u	u	u	u	u
20	6	3	3	u	u	u	3	u	u	u	1
21	7	4	u	u	u	u	u	11	u	u	7
22	--	--	--	--	--	--	--	--	--	--	--
23	--	u	u	--	--	--	--	--	u	u	7
24	u	u	3	u	u	u	u	u	u	u	u
25	u	4	u	u	u	u	u	u	u	u	u
26	5	2	u	u	u	11	--	12	u	u	u
27	8	0	3	11	u	9	2	14	u	u	u
28	8	4	u	12	u	6	3	--	u	u	u
29	--	--	u	--	--	--	--	u	u	u	u
30	--	--	u	--	--	--	--	u	2	u	u
31	u	5	5	u	u	u	u	6	u	u	u
32	u	4	u	u	u	u	u	8	8	u	u
33	6	3	u	11	u	u	3	--	u	u	u
34	6	4	2	9	-2	7	1	--	u	u	u
35	6	4	2	9	u	6	2	u	u	u	u
36	--	--	u	--	--	--	--	7	u	u	1
37	--	--	u	--	--	--	--	9	u	u	u
38	u	4	u	u	u	u	u	12	u	u	--
39	u	4	u	u	u	u	u	18	--	u	u
40	3	u	-2	u	u	u	4	4	--	u	u
41	4	4	u	6	-1	9	0	u	--	u	-1
42	7	--	--	8	u	5	2	7	--	u	4
44	--	--	u	--	--	--	--	--	--	u	u
45	u	u	-1	u	u	u	u	--	--	u	u
46	8	u	-2	u	u	u	u	--	--	u	u
47	7	3	-3	10	5	10	3	--	--	u	u
48	u	5	-2	9	8	7	2	--	--	--	--
49	8	7	u	8	u	5	3	--	--	--	--
52	u	--	--	--	u	u	u	--	--	--	--
53	u	--	--	12	4	--	u	--	--	--	--
54	9	3	--	11	4	10	6	--	--	--	--
55	9	--	--	10	1	7	5	--	--	--	--
56	12	--	--	14	u	7	--	--	--	--	--
57	--	--	--	--	--	--	--	--	--	--	--
58	--	--	--	--	--	--	--	--	--	--	--
59	--	u	u	--	u	--	u	--	--	--	--
60	9	--	--	u	u	11	--	--	--	--	--
61	9	4	3	u	7	8	6	--	--	--	--
62	9	u	--	--	8	9	u	--	--	--	--
63	--	--	3	u	u	11	--	--	--	--	--

Legend: u = Unreadable      (--) = Reading not attempted

TABLE VII

R-J<sub>1</sub> INTERVALS (MILLISECONDS)

Microphone Position Number	Case No.										
	1	2	3	4	5	6	7	8	9	10	11
1	u	36	26	--	--	--	--	--	--	32	--
2	u	u	24	--	--	--	--	--	--	33	--
3	u	u	23	--	--	--	--	--	--	31	--
4	u	u	23	--	--	--	--	--	34	31	--
5	u	u	u	--	--	--	--	--	36	32	--
6	38	37	23	--	--	--	--	--	33	32	--
7	u	36	23	--	--	--	--	--	28	33	--
8	39	37	24	--	--	u	--	--	30	32	--
9	u	u	22	--	--	--	--	--	33	33	--
10	u	36	u	--	--	u	--	--	u	31	--
11	u	35	--	--	--	u	--	--	30	32	--
12	u	35	--	--	--	u	--	u	30	32	--
13	36	34	--	--	--	--	--	35	30	31	--
14	--	u	--	--	--	--	--	31	31	34	--
15	41	u	24	--	--	u	--	33	u	u	--
16	u	39	22	--	--	u	--	--	30	u	--
17	u	u	21	u	22	u	u	--	30	32	u
18	u	36	19	u	21	u	u	33	32	32	u
19	u	32	19	31	20	u	u	32	34	u	u
20	42	36	21	31	19	u	u	31	32	30	46
21	u	35	21	u	21	u	u	31	30	32	45
22	--	u	24	--	--	--	--	--	--	--	--
23	--	u	24	--	--	--	--	--	35	u	47
24	u	38	23	33	21	u	37	32	35	30	49
25	u	40	22	32	21	u	36	31	34	28	47
26	u	35	19	31	19	u	--	30	30	30	44
27	39	34	18	31	18	u	32	33	30	32	46
28	u	u	20	31	18	u	u	--	u	29	46
29	--	--	27	--	--	--	--	34	u	u	49
30	--	--	23	--	--	--	--	31	u	28	49
31	u	39	21	34	21	u	38	33	u	u	47
32	u	u	u	32	21	u	36	34	u	31	u
33	u	u	u	29	19	u	37	--	u	32	46
34	42	35	20	31	19	u	33	--	u	u	50
35	44	33	19	31	16	u	28	35	u	u	48
36	--	--	24	--	--	--	--	32	u	u	44
37	--	--	22	--	--	--	--	33	u	u	u
38	u	43	23	34	21	u	38	33	u	u	--
39	u	41	22	33	21	u	39	34	--	u	46
40	u	36	23	30	20	u	36	u	--	u	43
41	42	34	u	31	19	u	34	35	--	u	43
42	u	--	--	30	u	u	27	34	--	u	48
44	--	--	22	--	--	--	--	--	--	u	48
45	u	43	22	34	21	u	37	--	--	u	48
46	u	42	22	33	20	u	36	--	--	u	48
47	u	u	21	32	u	u	33	--	--	u	48
48	43	34	19	32	u	36	33	--	--	--	--
49	u	34	19	31	u	34	28	--	--	--	--
52	u	--	--	--	21	u	38	--	--	--	--
53	44	--	--	34	20	--	37	--	--	--	--
54	u	u	--	33	u	38	36	--	--	--	--
55	u	--	--	33	u	36	u	--	--	--	--
56	u	--	--	u	u	35	--	--	--	--	--
57	--	--	--	--	--	--	--	--	--	--	--
58	--	--	--	--	--	--	--	--	--	--	--
59	--	46	u	--	23	--	38	--	--	--	--
60	45	--	--	36	21	40	--	--	--	--	--
61	u	44	22	u	19	36	u	--	--	--	--
62	u	u	--	--	u	35	u	--	--	--	--
63	--	--	27	u	u	34	--	--	--	--	--

Legend: u = Unreadable

(--) = Reading not attempted

TABLE VIII

R-J<sub>2</sub> INTERVALS (MILLISECONDS)

Microphone Position Number	Case No.										
	1	2	3	4	5	6	7	8	9	10	11
1	60	u	64	--	--	--	--	--	--	u	--
2	58	u	63	--	--	--	--	--	--	62	--
3	58	51	63	--	--	--	--	--	--	68	--
4	60	u	63	--	--	--	--	--	66	63	--
5	60	u	60	--	--	--	--	--	67	67	--
6	58	u	62	--	--	--	--	--	67	69	--
7	56	u	59	--	--	--	--	--	62	69	--
8	62	u	67	--	--	u	--	--	66	62	--
9	61	u	63	--	--	--	--	--	65	62	--
10	59	u	61	--	--	u	--	--	67	61	--
11	57	51	--	--	--	u	--	--	64	u	--
12	56	u	--	--	--	u	--	64	63	66	--
13	u	52	--	--	--	--	--	69	67	u	--
14	--	53	--	--	--	--	--	64	65	u	--
15	64	u	69	--	--	u	--	67	66	65	--
16	64	53	64	--	--	u	--	--	68	64	--
17	61	u	64	u	u	u	u	--	u	60	67
18	61	53	59	70	61	63	u	65	u	u	69
19	61	53	58	71	57	59	u	65	65	u	65
20	61	u	58	72	59	61	50	66	66	u	u
21	57	u	61	71	60	62	49	66	68	62	u
22	--	u	u	--	--	--	--	--	68	58	69
23	--	u	66	--	--	--	--	--	68	56	71
24	63	53	65	u	61	u	u	65	68	54	73
25	59	55	u	u	61	66	u	63	66	u	u
26	57	51	62	71	u	63	--	65	68	61	69
27	60	49	56	68	57	61	u	69	u	59	u
28	58	52	56	70	59	58	51	--	u	56	71
29	--	--	70	--	--	--	--	65	69	58	73
30	--	--	69	--	--	--	--	62	u	u	73
31	68	57	65	u	65	u	u	64	u	u	71
32	63	55	u	u	63	66	55	65	u	56	71
33	60	53	u	68	u	u	53	--	u	62	u
34	61	50	59	70	59	63	u	--	u	61	74
35	64	49	57	69	59	61	49	67	u	56	74
36	--	--	71	--	--	--	--	64	u	u	72
37	--	--	69	--	--	--	--	64	u	u	u
38	68	u	65	u	66	u	59	64	u	56	--
39	63	55	64	u	65	65	61	64	--	62	71
40	58	53	63	69	62	63	54	60	--	58	71
41	60	u	u	68	u	63	u	u	--	60	71
42	62	--	--	69	60	60	53	73	--	55	u
44	--	--	67	--	--	--	--	u	--	u	72
45	70	u	66	u	65	67	61	u	--	60	73
46	62	58	65	u	64	65	59	--	--	u	u
47	59	u	65	72	62	65	54	--	--	u	70
48	59	u	61	70	63	64	55	--	--	--	--
49	59	50	62	u	61	60	u	--	--	--	--
52	u	--	--	--	67	68	64	--	--	--	--
53	64	--	--	75	64	--	59	--	--	--	--
54	u	u	--	74	62	64	58	--	--	--	--
55	59	--	--	73	63	62	54	--	--	--	--
56	78	--	--	76	63	62	--	--	--	--	--
57	--	--	--	--	--	--	--	--	--	--	--
58	--	--	--	--	--	--	--	--	--	--	--
59	--	u	68	--	70	--	59	--	--	--	--
60	64	--	--	u	67	67	--	--	--	--	--
61	u	u	68	80	64	65	62	--	--	--	--
62	u	67	--	--	63	67	u	--	--	--	--
63	--	--	u	81	62	66	--	--	--	--	--

Legend: u = Unreadable (--) = Reading not attempted

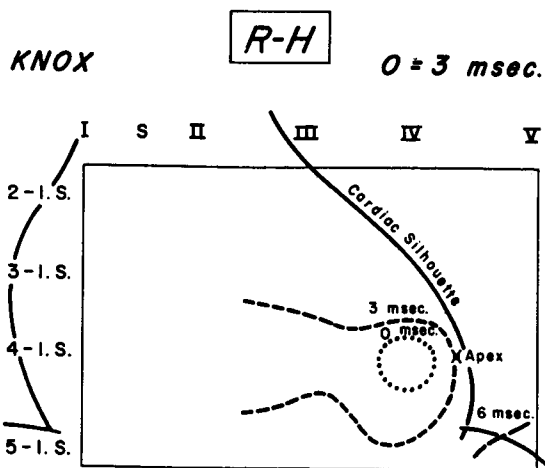


Figure 37

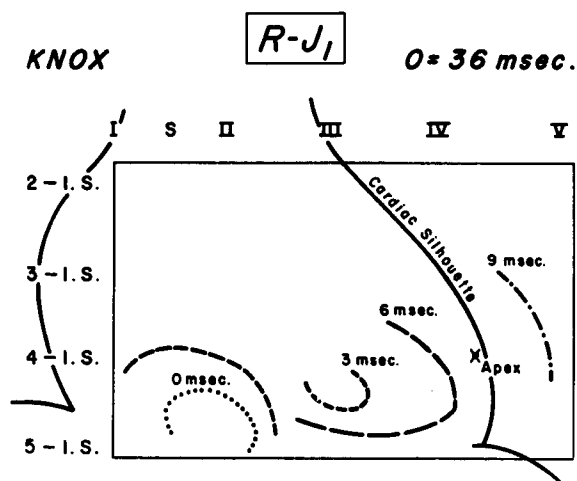


Figure 38

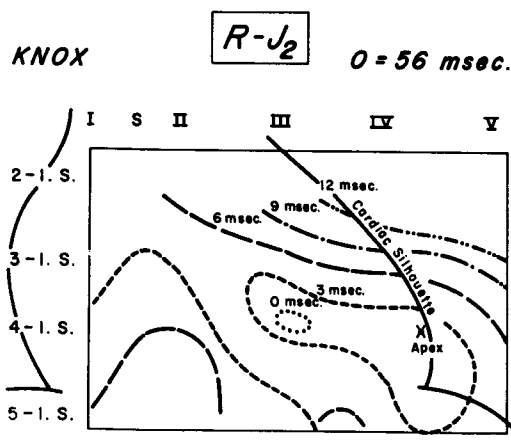


Figure 39

By studying the iso-temporal contour lines, it was possible to determine the propagation time of each of the vibrocardiographic waves over the precordium.

The speed of propagation of " $J_1$ " and " $J_2$ " on the precordium

was measured perpendicularly to the iso-temporal lines. As these lines enclose areas elongated in the direction of the longitudinal axis of the heart, we could measure two velocities; the fastest, along this preferential axis, where the iso-temporal lines are most widely separated, and the slowest, where these lines are closest to each other.

### 3.2.1.1 Results

Tracings permitting identification of the VbCG waves were recorded over a limited area which corresponds approximately to the projection of the heart on the anterior chest wall as determined by supine X-ray measurements. The interpretation of the tracings became increasingly difficult on approaching the limits of this area and outside it they became unreadable. The area extending from the 4th to the 5th left intercostal space, near the sternum between positions II and III yielded the best tracings and also demonstrated the least variations introduced by changes in the position of the microphone, thus confirming the selection of this position previously chosen as the standard recording area.

Comments concerning the identification of vibrocardiographic waves versus position of the microphone follows:

"H" Wave: The "H" wave was the most difficult to identify and only could be located accurately in a small area which extended between the 4th and the 5th intercostal spaces from the PMI to the left lower sternal border. The "R-H" interval varied from 3 to 18 milliseconds (Figure 37).

"J<sub>1</sub>" Wave: The "J<sub>1</sub>" wave was detectable in the area below the third interspace from the sternal border to the mid-clavicular line. The shortest "R-J<sub>1</sub>" interval was found between the fourth and the fifth intercostal spaces and measured 16 to 36 milliseconds (Figure 38).

"J<sub>2</sub>" Wave: The "J<sub>2</sub>" wave was, in most cases, easily identified over the whole precordial projection of the cardiac silhouette. The shortest "R-J<sub>2</sub>" interval was also found from the fourth to the fifth left intercostal space, near the sternum, between lines II and III (Figure 39). The shortest "R-J<sub>2</sub>" intervals ranged from 49 to 66 milliseconds. In 9 of the 11 subjects it was possible to draw iso-temporal lines. In the two other subjects the timing points were so irregularly scattered that it was not possible to draw iso-temporal lines connecting them.

In one subject waves resembling the left precordial "J<sub>1</sub>" and "J<sub>2</sub>" as recorded at their "zero points" were found at the xyphoid area. In this case the "zero points" for "J<sub>1</sub>" and "J<sub>2</sub>" were placed at the outer limit of their usual location.

The fastest velocity of "propagation" for " $J_1$ " and " $J_2$ ", along their preferential direction, could be measured only from the source to the 3 milliseconds iso-temporal line because after this point the wave was dispersed rapidly beyond the area studied. The fastest speeds measured for " $J_1$ " varied from 10 meters/second (m/sec) to 26.7 m/sec. in different subjects with an average of 18.1 m/sec. For " $J_2$ " the velocities varied from 10 m/sec. to 23.2 m/sec with an average of 15.1 m/sec. The slowest velocity noted occurred along an axis pointing upwards and to the left. In this direction it ranged in different subjects between 5.8 m/sec and 13.3 m/sec for " $J_1$ " with an average of 9.9 m/sec; and " $J_2$ " it varied between 3.3 m/sec and 8.9 m/sec with an average of 6.9 m/sec.

The maximal and minimal velocities of each wave for the individual subject are indicated in the table below.

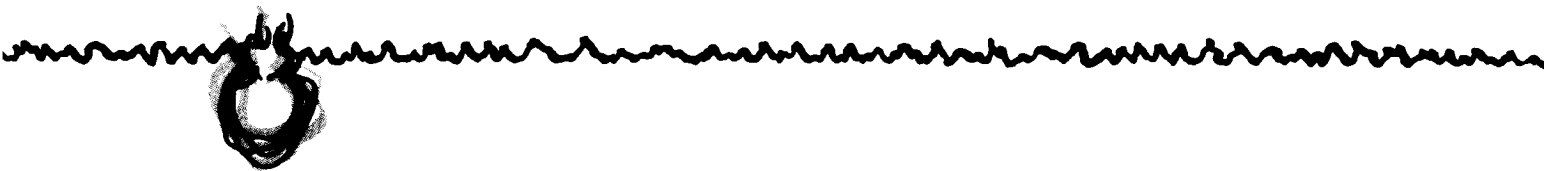
TABLE IX  
PROPAGATION VELOCITY OF " $J_1$ " AND " $J_2$ " WAVES  
IN INDIVIDUAL SUBJECTS  
(Meters per Second)

<u>Maximal Propagation</u>		<u>Subject</u>	<u>Minimal Propagation</u>	
<u><math>J_1</math></u>	<u><math>J_2</math></u>		<u><math>J_1</math></u>	<u><math>J_2</math></u>
10.0	23.2	1	10.0	3.3
26.3	20.0	2	5.8	6.7
23.2	13.3	3	11.6	6.7
20.0	10.0	4	10.0	8.3
23.2	16.7	5	11.6	6.7
20.0	23.2	6	10.0	8.9
13.3	U	7	6.7	6.7
26.7	10.0	8	10.0	8.3
U	20.0	9	13.3	6.7
		10		
18.1 Av.	15.1 Av.		9.9 Av.	6.9 Av.

U= Unreadable

### 3.2.1.2 Discussion

In 1952 von Gierke,<sup>22</sup> et al. studied the physics of vibrations in living tissues in the frequency range of 0 to 20 K c.p.s. They proposed the theory that the propagation of energy in body tissue is like that in an elastic viscous compressible medium. They found three (3) types of waves: compression, shear and surface waves, each having different impedance and transmission values. Von Gierke<sup>23</sup>, in 1959, further studied the impedance, elastic reactance and transmission of such energy in terms of frequency. Compression waves have a constant sound velocity of about 1500 m/sec (1.5 m/msec) and therefore can be considered as nearly instantaneous. However, most of the vibratory energy is propagated in the form of transverse shear waves with a velocity of 20 m/sec at 200 c.p.s. (2 cm/msec) and increases approximately with the square root of the frequency. Some of the energy was found to be propagated along the body surface in the form of surface waves as predicted by Oestreicher<sup>24</sup> in 1951. The phase and group velocity of these waves were found to be of the same order as shear waves. Up to approximately 50 c.p.s. the velocity was around 2-3 cm./msec and at approximately 150 c.p.s. it was 10-12 cm./msec.



In 1962 Faber and Burton<sup>25</sup> studied the spread of heart sounds over the chest wall. They made simultaneous recordings with several microphones glued to the chest to eliminate the effect of changes in pressure on phase shift. The microphones used, however, were flat only from 20 to 200 c.p.s. The velocities were calculated by measuring the distance, in time of arrival at two points separated by a known distance. They were found to range from 8.8 to 23.3 m/sec with an authentic mean of 14.8 m/sec (1.5 cm/msec). Geometrical determination of the secondary source of these vibrations was undertaken since the velocities indicated that the sounds could not arise by rectilinear propagation from their power of origin at the heart valves. The "mitral area" was found to correspond with the point of contact of the tip of the left ventricle with the thoracic wall but the secondary sources for other heart sounds could not be determined.

More recently, Faber<sup>25</sup> has reported on the damping of sound at the chest surface by applying an external source of sound to the skin of the thorax. The purpose was to find out whether the heart sounds spread in two dimensions over the chest wall from their auscultatory areas or in 3 dimensions directly from their origins deep in the body. A geometrical equation, representing the damping in soft tissues and ribs, was found to be proportional


to the square root of the frequency and suggested that the intensity of sounds was inversely proportional to the distance traveled and not to the square root of the distance traveled. This indicated that heart sounds travel from the heart to their auscultatory areas on the chest wall and from there over the chest surface.

In 1963 Zalter and Luisada<sup>26</sup> studied the acoustic transmission characteristics of the thorax by picking up the precordial vibrations from a specially constructed intracardiac microphone (Bertrand). It was found that the transmission characteristic of the thorax was linear with respect to frequency, and that the amplitude of the vibrations transduced from the intact chest wall was a function of their proximity to the source; these results agreeing with those of Dock<sup>27</sup> and Bertrand.<sup>28</sup> The transmission loss was 20-40 db for the various parasternal areas in the supine position, the attenuation being great below 100 c.p.s. and highly dissipated above 300 c.p.s. The major response was particularly at 150-200 c.p.s. for dogs.

It appears to have been established, therefore, that compression waves are instantaneous, and that any wave with a measurable speed must be a shear wave or a surface wave. The rate of propagation of shear and surface waves

increases as the frequency increases (square root) but for the range of frequencies being studied (2-1000 c.p.s.) travels at the approximate average rate of 15 meters/second or 1.5 cm/msec. If the distance between the iso-temporal lines determined in this study be related to the time elapsed from the peak of R, then the velocity of the "J<sub>1</sub>" wave would average 18 m/sec and for "J<sub>2</sub>" 15 m/sec — figures which agree well with those quoted.<sup>22,23,25</sup> The rapid deterioration of the wave form is consistent with the known rapid transmission loss as the proximity from the source diminishes.<sup>27</sup>


However, the wide difference in the transmission velocities of the "J<sub>1</sub>" and "J<sub>2</sub>" waves over the precordium in the different subjects, the unexplained transmission direction (inferiorly and to the left), and the presence in two of our subjects of points that were irregularly scattered and could not be plotted into iso-temporal lines makes it questionable whether we are recording a simple "spreading" of the waves around their "secondary sources" or whether it is a more complex phenomenon not amenable to this kind of analysis. Much more work in this field will be necessary before the genesis of these wave forms will be thoroughly understood.



Examination of the iso-temporal line charts suggests, however, that the vibrocardiographic waves make their initial appearance on the chest surface in discrete areas. We have timed them as "zero points" and consider these zero points the "secondary sources" of the waves, the primary source being the heart.

#### 3.2.1.3 Summary

- \* Sixty-three vibrocardiograms were recorded in each of 11 athletes from a precordial area extending from the right sternal border to the left anterior axillary line and from the second to the fifth intercostal space.
  
- \* An area between the 4th to the 5th left intercostal spaces near the sternum was chosen as the standard location for the VbCG transducer because 1) the wave forms were most clearly delineated in this area, and 2) this area represents the location where the "H", "J<sub>1</sub>" and "J<sub>2</sub>" waves make their earliest appearance, as represented by the minimal delay recorded, and 3) because shifts in the microphone at this position produce the least changes in wave form.

- 
- \* Clear wave forms were largely confined to the projection area of the cardiac silhouette onto the precordium.
  - \* In nine (9) subjects construction of iso-temporal lines permitted the calculation of the speed of transmission of the "J<sub>1</sub>" and "J<sub>2</sub>" waves across the surface of the chest at an approximate rate of 15 to 18 meters/second; in agreement with previous studies on the rates of transmission of sound through animal tissue.

However, it was not possible to prove whether the vibrocardiographic waves merely spread over the precordium from their "secondary sources" (areas of earliest appearance) or whether the phenomenon is a much more complex process which is not amenable to this method of analysis.

### 3.2.2 Correlation of the VbCG and ECG with the Functional Status of Exercised Normal Males and those with Ischemic Heart Disease

The clinical procedure in most frequent use at the present time for the detection of coronary insufficiency is the two-step electrocardiographic exercise test. However, a recent double-blind study revealed 39% false positive and 12% false

negative tests.<sup>30</sup> Current reviews have also indicated the variabilities in the interpretation of electrocardiographic exercise tests.<sup>31,32</sup>

Previous studies in this laboratory<sup>33</sup> have demonstrated that the vibrocardiogram provides a more reliable index of cardiac function than the electrocardiographic two step test. It was found that changes in the vibrocardiographic intervals corresponding to isometric contraction and ejection, when compared as a ratio, served to distinguish the exercise response of normal subjects from patients with coronary insufficiency.

This report provides data from seven subjects undergoing the single two step test and 128 subjects who have performed the double two step test.

Vibrocardiograms were obtained from adult patients by the recording technique described earlier in this report. A double two step exercise test was performed and ECG's and VbCG's were obtained at resting control levels, immediately after exercise and after a five minute recovery period. Blood pressure and heart rate measurements were also obtained. Isometric contraction time ( $H-J_2$  interval) and ejection time ( $J_2-L$  interval) were recorded and the ratio between these two were calculated ( $H-J_2/J_2-L$  ratio).

The group studied consisted of 128 patients who have been periodically evaluated. Their clinical histories were well known and X-rays and ECG's along with blood and urine studies were available. Classification was based on clinical evaluation, radiologic studies and resting, exercise, and ECG's. The major divisions of the classification for patients in vibrocardiographic exercise testing appear as follows:

- I. Normal
  - A. Sedentary
  - B. Ordinary
  - C. Athlete
- II. Functionally Normal (Class I-A, no symptoms, no restrictions).
  - A. No history of cardiovascular disease, abnormal ECG
  - B. History of heart disease
    - 1. Ischemic heart disease
    - 2. Hypertensive heart disease
    - 3. Valvular heart disease
- III. Functionally Abnormal (symptoms and/or restrictions and/or cardiac drugs)
  - A. Ischemic heart disease
  - B. Hypertensive heart disease
  - C. Valvular heart disease

Data obtained from this study of the correlation of ECG and VbCG with exercised functional status are present below for Double Master and Single Master tests.

DOUBLE MASTER

<u>Type of Patient</u>	<u>Number of Cases</u>	<u>Data Record</u>	<u>Normal Response</u>	<u>Abnormal Response</u>	<u>Per Cent Correlation</u>
Normal	89	ECG	80	9	90%
		VbCG	77	12	87%
Functionally Normal	39	ECG	22	17	56%
		VbCG	34	5	87%

SINGLE MASTER

<u>Type of Patient</u>	<u>Number of Cases</u>	<u>Data Record</u>	<u>Normal Response</u>	<u>Abnormal Response</u>	<u>Per Cent Correlation</u>
Normal	46	ECG	43	3	93%
		VbCG	43	3	93%
Functionally Normal	8	ECG	6	2	75%
		VbCG	7	1	87.5%
Functionally Abnormal	27	ECG	10	17	59%
		VbCG	4	23	85%

#### 3.2.2.1 Results

The correlation of the ECG and VbCG with the functional status of the patient using a double Master two step test was evaluated in 128 cases.

In 89 cases classified as normal, there was no significant difference between the results of the ECG or vibrocardiograph exercise test. The ECG was normal in 90 per cent, the VbCG normal in 87 per cent.

In 39 cases classified as functionally normal, the ECG exercise test agreed with the functional status in 56 per cent. The vibrocardiograph exercise test corresponded with the functional status in 87 per cent of the cases in this group.

The correlation of the ECG and VbCG with the functional status of the patient using a single Master two step test was evaluated in 81 cases.

In 46 normal patients there was no difference in the response to the ECG or VbCG exercise test. In a group of eight patients classified as functionally normal the ECG correlated with the clinical status in 75 per cent, the VbCG correlation in this group being 87 1/2 per cent.

In a group of 27 cases classified as functionally abnormal the ECG correlated with only 59 per cent, compared to 85 per cent correlation with the VbCG exercise test.

### 3.2.2.2 Conclusion

The VbCG correlates more closely than the ECG with the functional heart status of a group of 209 patients. This was particularly significant in the correlation of the functionally abnormal group using the single two step test, a group which cannot safely perform the double test; and also in the functionally normal group when using the double two step test. The results are graphically summarized in Figures 40 and 41 below.

*CORRELATION OF ECG AND VIBROCARDIOGRAM WITH FUNCTIONAL STATUS USING DOUBLE MASTER TWO STEP TEST (128 CASES)*

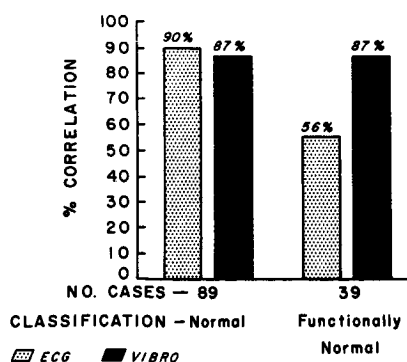


Figure 40

*CORRELATION OF ECG AND VIBROCARDIOGRAM WITH FUNCTIONAL STATUS USING SINGLE MASTER TWO STEP TEST (81 CASES)*

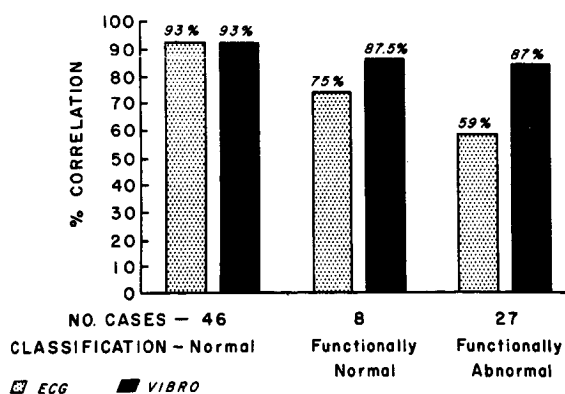


Figure 41

### 3.2.3 Study of the Vibrocardiogram in Athletes During Maximal Exercise


The need for a simple, reliable method of stressing the heart in order to distinguish between normal and abnormal function, has produced standard exercise tests such as the two-step test. The electrocardiographic tests have proved useful but probably do not permit an accuracy of more than 80 per cent<sup>34</sup> and are limited to changes in the ECG, attributed to ischemia, usually found in more advanced disease states.

Tests of the mechanical activity of the heart offer an additional approach in terms of the forces generated during contraction and relaxation. To this end, ballistocardiography,<sup>35</sup> apexcardiography,<sup>36</sup> accelerography,<sup>37,38</sup> and vibrocardiography,<sup>39</sup> are being more intensively studied. Previous work with the vibrocardiographic exercise test in ischemic heart disease indicated that it was at least as sensitive as the two-step test in distinguishing normal from abnormal subjects,<sup>40</sup> (as discussed in the previous section of this document). Using measurements made from the VbCG, the intervals corresponding to isometric contraction and ejection, expressed as a ratio, can be compared before and after exercise,<sup>41</sup> (see Section 2.2). In known normal subjects this ratio increased after exercise, and in subjects with

clinically established ischemic heart disease the ratio decreased with exercise. The reasons for this difference in the interval ratio response have not been proved. However, the opposing directions of the ratios may be related to differences in the volume of the normal and ischemic ventricles in response to exercise.<sup>42</sup> Recent studies have indicated that the ejection time is a function of the cardiac output and not the heart rate.<sup>43</sup> Thus the interval ratio expresses this ability of the normal heart to shorten ejection time.

A recent paper by Messer, et al.,<sup>44</sup> points up the value of the measurement of ejection time in the assessment of cardiac function. Weissler<sup>43</sup> has also recently pointed out that the decrease in the ejection time index accompanied a decrease in cardiac output. Thus a simple technique for measuring ejection time may serve as a valuable method of estimating heart function.

The purpose of this correlation study was to test the interval ratio response to exercise compared with standard methods of assessing heart performance, particularly with reference to oxygen consumption.



Subjects considered as athletes were actively engaged in strenuous university athletic or were highly trained, active long distance cyclists. All subjects were screened to exclude cardiac abnormality on basis of history, physical examination, and ECG. Chest X-rays were obtained where indicated. Exercise testing was carried out on the bicycle ergometer and treadmill. Subjects were given preliminary exercise runs one (1) to seven (7) days prior to an actual test to familiarize them with the technique.

Athletes were studied in a near basal, post absorptive state. Expired air was collected through a low friction Rudolph valve into Douglas bags, and the volumes measured by a dry gas meter. Bicycle exercise testing was conducted in the following manner using a bicycle ergometer: Control data were obtained in the supine position and while sitting on the bicycle with both feet on the resting bar. A control hemoglobin was determined in triplicate. In order to achieve a "steady state", a "warm up" at a low level of exercise was performed for four to five minutes before increasing the work load. Progressive increases in the levels of exercise were accomplished by increasing the pressure of the friction brake of the ergometer. Tests were carried out until the subject, because of marked fatigue, was unwilling or unable to proceed. Full minute samples of expired air were collected at successive levels of exercise

as new steady states were reached. Stable pulse rates were used as guides.<sup>45</sup> During the final 15 seconds of the gas collection a record was obtained of the ECG, VbCG, pulse rate, and blood pressure. Recovery studies were performed after 5 and 15 minutes of rest. Recently, we determined that passing the VbCG through a 2.5 cycle high pass filter largely eliminated baseline drift due to rapid respiration and allowed satisfactory tracings for continuous wave identification and amplitude changes during exercise.

Treadmill exercise testing was performed on a W. E. Quinton treadmill Model No. 18-49-C utilizing the criteria outlined by Bruce<sup>46</sup> with a speed of 1.73 mph at a grade of 10 per cent for a submaximal test or a pulse rate less than 180. Sampling times and techniques were performed as with the bicycle ergometer.

After a suitable recovery period maximal exercise was then performed by running the treadmill at 4.5 mph at an elevation of 15 degrees until a pulse rate greater than 180 was achieved or until the subject became exhausted. This approach offered a contrast between mild exercise, suitable for older subjects and subjects with abnormalities of the cardiovascular system, and heavy exercise, in the same subject. It is hoped that a submaximal exercise load (with individual variations) can be determined which will

prove safe when abnormality exists but which will stress the heart sufficiently to reveal sub-clinical disease.

In all of the studies, the oxygen, carbon dioxide, and nitrogen concentrations were obtained by the Scholander technique of direct gas analysis.<sup>47</sup> Oxygen consumption was calculated with the standard oxygen consumption formula.<sup>48</sup>

Blood pressure was obtained by direct sphygmomanometry. The pulse rate was continually recorded by an Electronics for Medicine (E/M) audio output as obtained from the R wave of the ECG. A bipolar ECG lead from both anterior axillary lines was continuously recorded. A VbCG was recorded continuously during the testing using the LTV-2 transducer strapped to the chest wall in the 4th intercostal space in the left parasternal area.

Recordings were obtained on an E/M oscilloscope recorder at a speed of 200 mm/sec, as shown in Figure 42.

Simultaneous photographic tracings (Figure 43) were obtained with a Tektronix oscilloscope equipped with polaroid camera attachment. Recordings at a speed of 250 mm/sec (50 milliseconds/cm) were obtained with this technique.

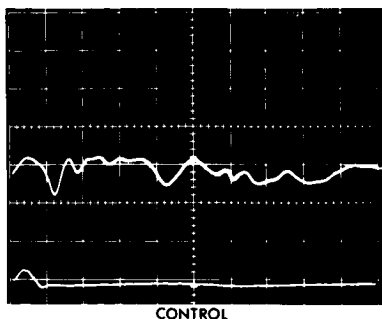


Figure 42

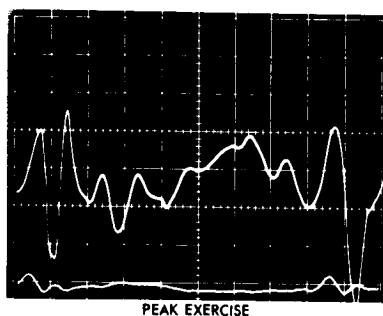



Figure 43

In addition to the vibrocardiographic measurements obtained during exercise, it was desired to correlate ventricular slope, time tension index, and mean systolic ejection rate, with the exercise response of the subject. These measurements were made as follows:

1. The time tension index: This index was the product of the ejection time and the mean systolic pressure. The ejection time was determined from the vibrocardiographic  $J_2$ -L interval and the mean systolic pressure



obtained by adding one-third of the pulse pressure to the diastolic pressure of the sphygmomanometrically obtained blood pressure measurements. Multiplying the index so obtained by the heart rate gave the minute index.

2. The ventricular slope was obtained by dividing the diastolic arterial pressure by the isometric contraction time. This index provided an indication of the average rate of pressure change during the isometric contraction interval.
3. The mean systolic ejection rate was determined by dividing the stroke volume as obtained by the Lamb formula by the ejection time ( $J_2-L$ ). This index yields an indication of the rate of ejection from the left heart. As the Lamb formula provides only an indication of cardiac output at peak exercise, the measurements are shown for this level only. These parameters were determined at the successive exercise levels and correlated with the oxygen uptake /BSA and the vibrocardiographic interval ratio.

The use of the bicycle ergometer provides accurate interpretation of calibrated work produced in kilopondmeters.\* A constant cycling rate (50/minute) is established using a metronome adjusted for 100 beats per minute. With these factors as constants the "track distance" covered is 300 meters/minute; therefore one kilopond (1 kp) = 300 kpm/minute.<sup>50</sup> The total expired gas volumes at increasing exercise levels and recovery were recorded and O<sub>2</sub> and CO<sub>2</sub> percentages were determined by Scholander technique. Oxygen consumption was determined by the formula<sup>51</sup>

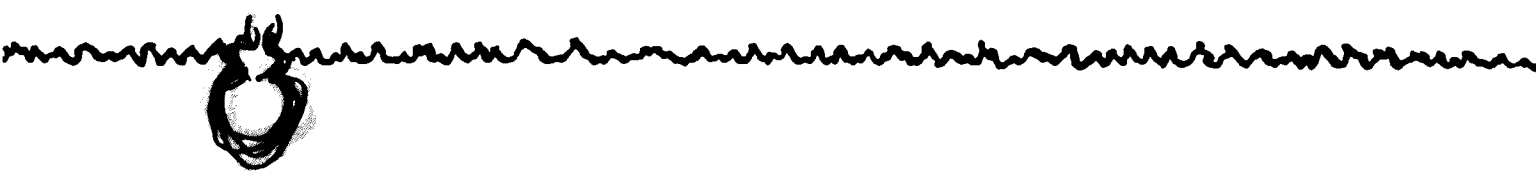
$$(1) \text{VO}_2 = \text{VE} \frac{\text{FI}_{\text{O}_2}(1-\text{FE}_{\text{CO}_2}) - \text{FE}_{\text{O}_2} - (1-\text{FI}_{\text{CO}_2})}{(1-\text{FI}_{\text{O}_2} - \text{FI}_{\text{CO}_2})}$$

Body surface area (BSA), as determined from Dr. Bois' nomogram, reflects the influence of subject's height and weight and the quotient resulting from the ratio VO<sub>2</sub>/BSA appears to bear a linear relationship to increased work demands.<sup>52</sup>

Cardiac output may be estimated approximately by the product of the pulse rate and pulse pressure.<sup>53</sup> An estimated cardiac output may also be obtained by calculating the O<sub>2</sub> capacity (Hgb x 1.34) and applying the Fick formula

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\*A kilopond is the force acting on the mass of one kilogram at normal acceleration of gravity.




using the measured  $O_2$  consumption and an assumed AV difference.<sup>49</sup> We are also preparing to measure cardiac output directly by the dye dilution technique.

The exercise testing program as described in this report represents a highly complex procedure requiring the coordination and integration of many skills, activities and equipment maintenance and preparation. The following represents the minimal personnel required for the described physiological exercise testing procedure and their assigned duties, all of which are performed simultaneously during an experiment.

Research cardiologist - M.D.

Responsible for cardiovascular history and physical examination screening, the conduct of the exercise test, supervision of the patient's response to exercise, obtaining records at suitable levels of exercise and, monitoring of the pulse, blood pressure and electrocardiographic changes.



### Laboratory Technician


Responsible for gas collection and appropriate gas sampling and minute ventilation measurements. Primary assistant to M. D. cardiologist in the general conduct of the test and obtaining records.

### Electronic Technician

Preparation and supervision of electronic equipment utilized for testing procedure. The apparatus frequently requires adjustment during the actual conduct of experiments. Also utilized as data recorder and timekeeper.

#### 3.2.3.1 Results

The two large tables presented later in this "Results" discussion contain the experimental data obtained from twenty-one athletic subjects. Data were recorded at conditions of rest, successive levels of exercise up to their maximum, and during recovery. Parameters recorded include blood pressure, pulse pressure, heart rate, oxygen consumption and vibrocardiographic "H-J<sub>2</sub>" and "J<sub>2</sub>-L" intervals. These data were recorded in absolute units and per cent change from resting conditions and



correlated with the subject's oxygen uptake per unit of body surface area ( $\text{cc}/\text{cm}^2/\text{min}$ ). Oxygen uptake was chosen as the standard correlative parameter because it has been shown to be linearly related to cardiac output.

The above mentioned correlation involved the plotting of absolute value and per cent change data versus oxygen consumption. An "equitable curve" was then hand-drawn through each set of plotted data in an effort to present average correlative data. These plots are presented in the latter part of this section, as indicated below.

Figure numbers followed by an "A" denotes absolute value data. A "B" denotes per cent (%) change data. We are now in process of statistically analyzing these data by use of least-squares polynomial curve fitting techniques.

Figures 44 A & B - Heart Rate vs.  $\text{O}_2$  Consumption

Figures 45 A & B - Pulse Pressure vs.  $\text{O}_2$  Consumption

Figures 46 A & B - " $\text{H-J}_2$ " vs.  $\text{O}_2$  Consumption

Figures 47 A & B - " $\text{J}_2\text{-L}$ " vs.  $\text{O}_2$  Consumption

Figures 48 A & B - " $\text{H-J}_2$ "/" $\text{J}_2\text{-L}$ " Ratio vs.  $\text{O}_2$  Consumption

Figures 49 A & B - Time Tension Index vs.  $\text{O}_2$  Consumption

Figures 50 A & B - Minute Time Tension Index vs.  $\text{O}_2$  Consumption

Figures 51 A & B - Ventricular Slope vs.  $\text{O}_2$  Consumption

Figures 52 A - Mean Systolic Eject. Rate vs.  $\text{O}_2$  Consumption

Figures 53 A & B - Pulse Press x Heart Rate vs.  $\text{O}_2$  Consumption

It is apparent from inspection of the above referenced data that as the subjects progressed from resting conditions to

FIGURE 4A-A  
HEART RATE AS A FUNCTION OF  $O_2$  CONSUMPTION/BSA

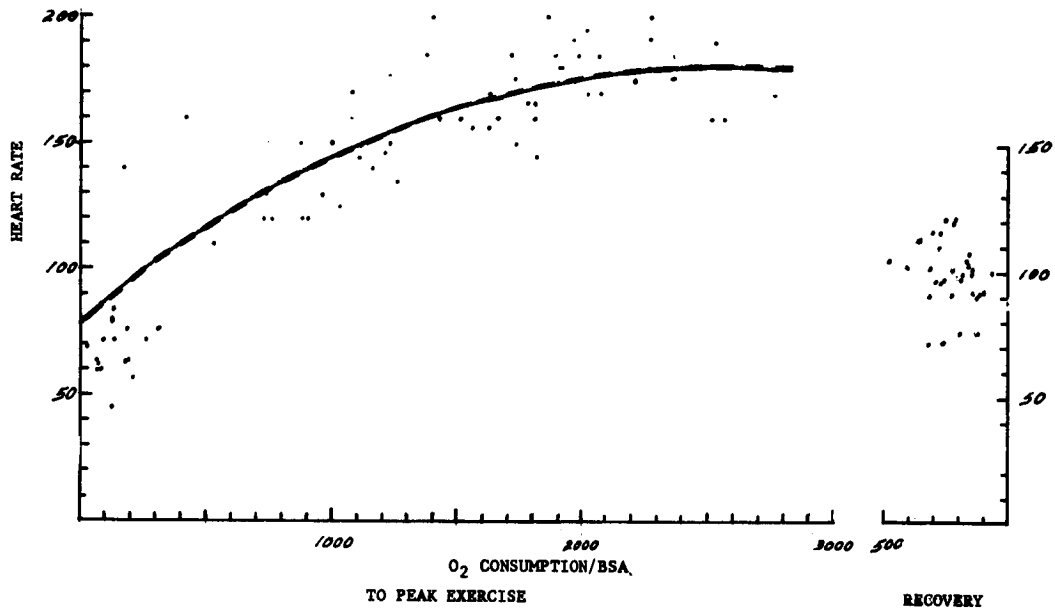


FIGURE 4A-B  
CHANGE IN HEART RATE AS A FUNCTION OF INCREASE IN  $O_2$  CONSUMPTION/BSA

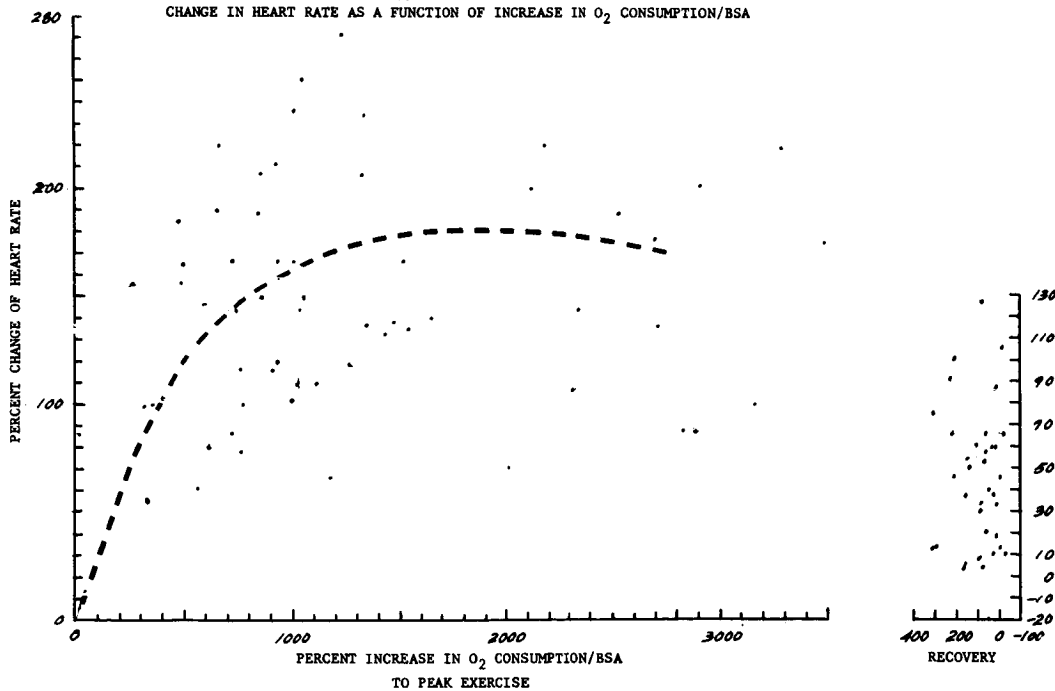


FIGURE 45-A  
PULSE PRESSURE AS A FUNCTION OF  $O_2$  CONSUMPTION/BSA

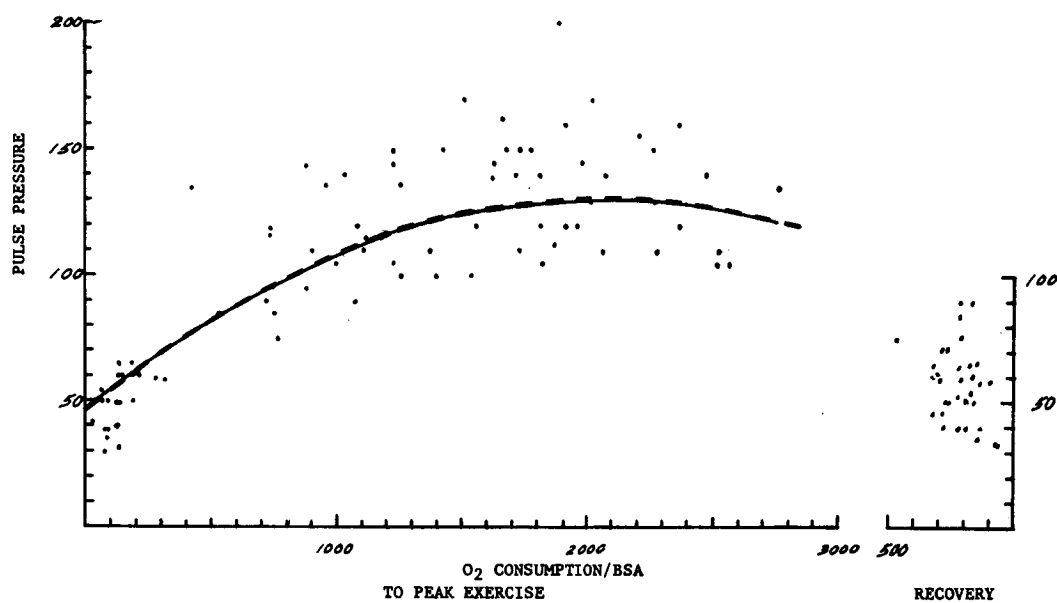


FIGURE 45-B  
CHANGE IN PULSE PRESSURE AS A FUNCTION OF INCREASE IN  $O_2$  CONSUMPTION/BSA

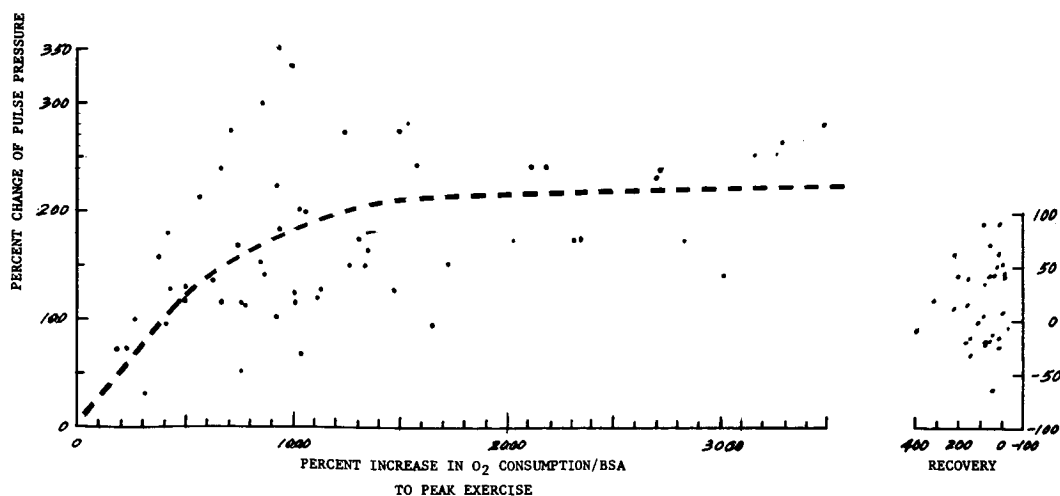


FIGURE 46-A  
H-J<sub>2</sub> AS A FUNCTION OF O<sub>2</sub> CONSUMPTION/BSA

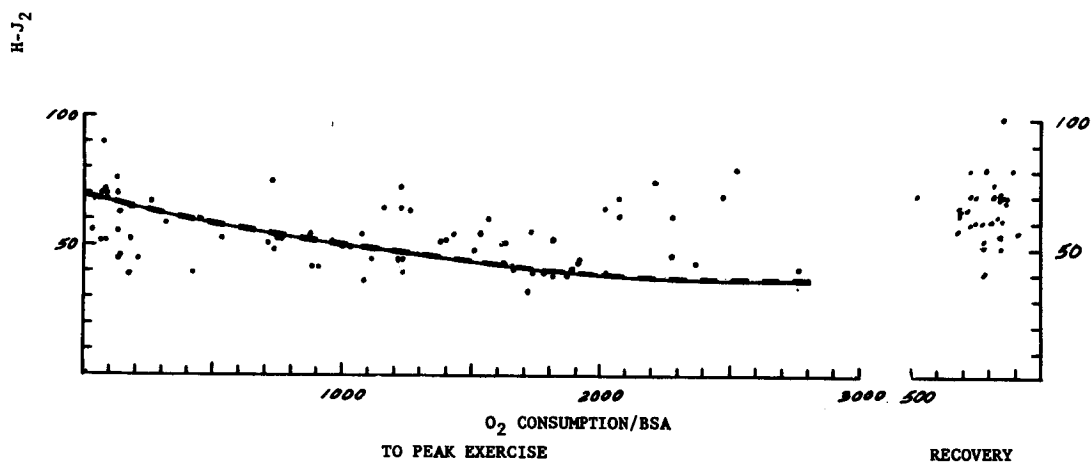


FIGURE 46-B  
CHANGE IN H-J<sub>2</sub> AS A FUNCTION OF INCREASE IN O<sub>2</sub> CONSUMPTION/BSA

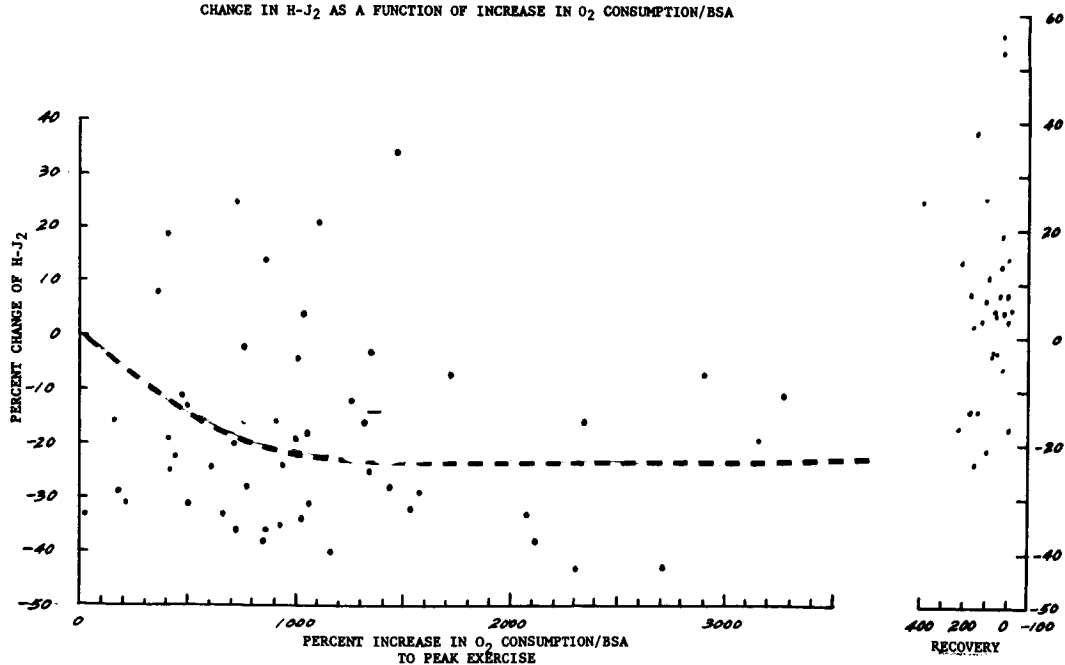




FIGURE 47-A  
 $J_2-L$  AS A FUNCTION OF  $O_2$  CONSUMPTION/BSA

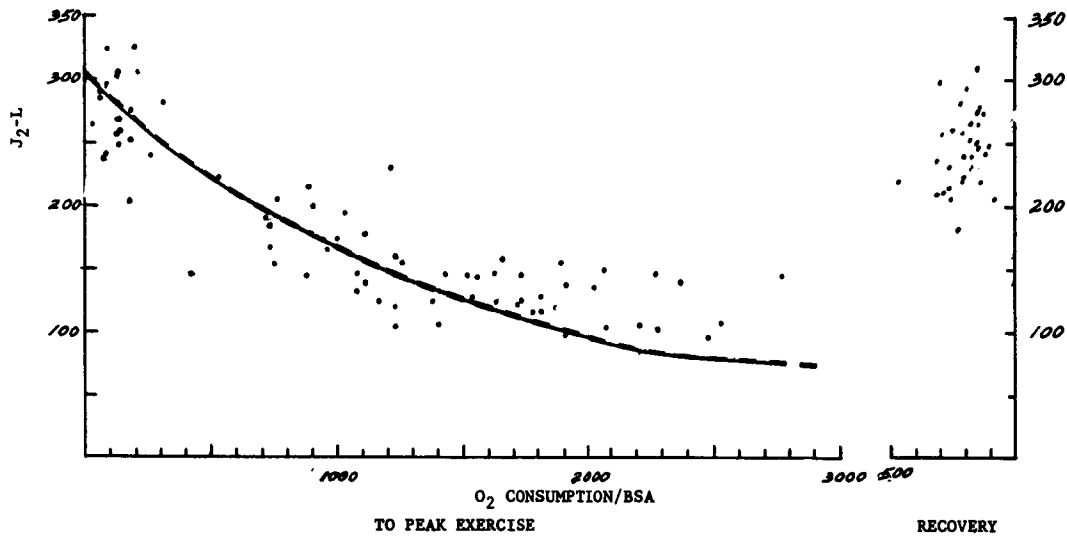


FIGURE 47-B  
CHANGE IN  $J_2-L$  AS A FUNCTION OF INCREASE IN  $O_2$  CONSUMPTION/BSA

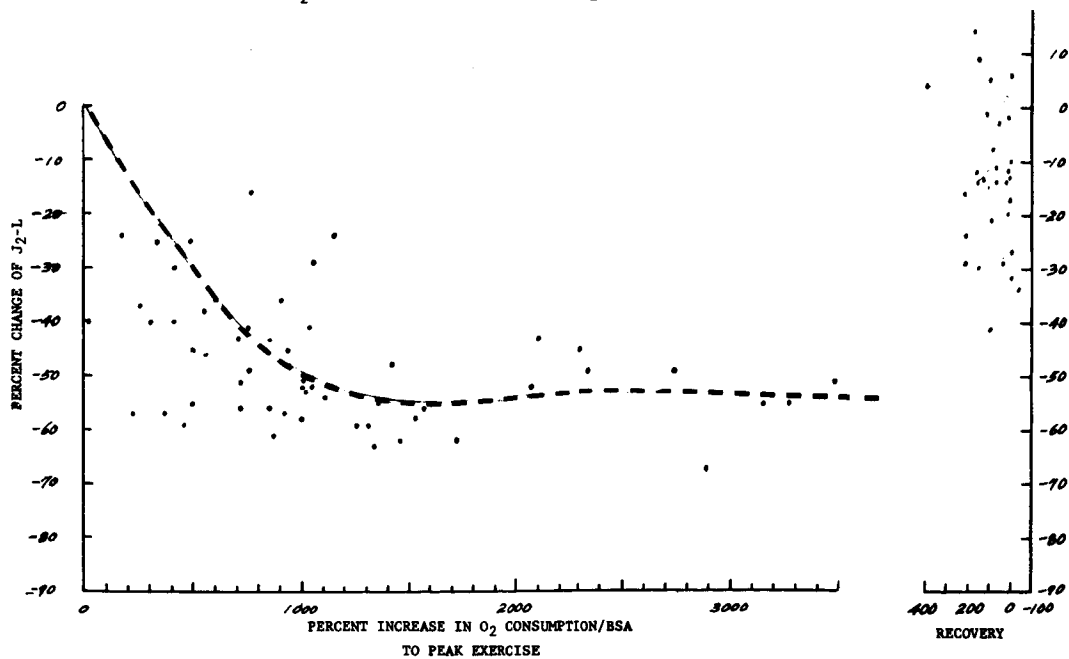




FIGURE 48-A  
H-J<sub>2</sub>/J<sub>2</sub>-L RATIO AS A FUNCTION OF O<sub>2</sub> CONSUMPTION/BSA

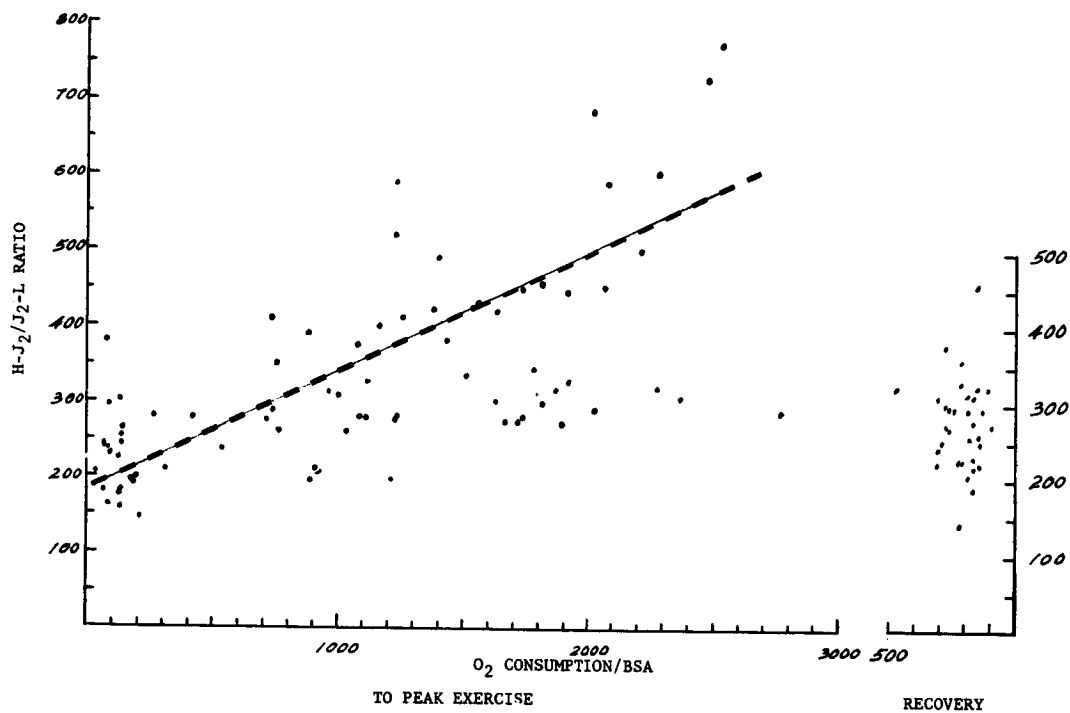


FIGURE 48-B  
CHANGE IN H-J<sub>2</sub>/J<sub>2</sub>-L RATIO AS A FUNCTION OF INCREASE IN O<sub>2</sub> CONSUMPTION/BSA

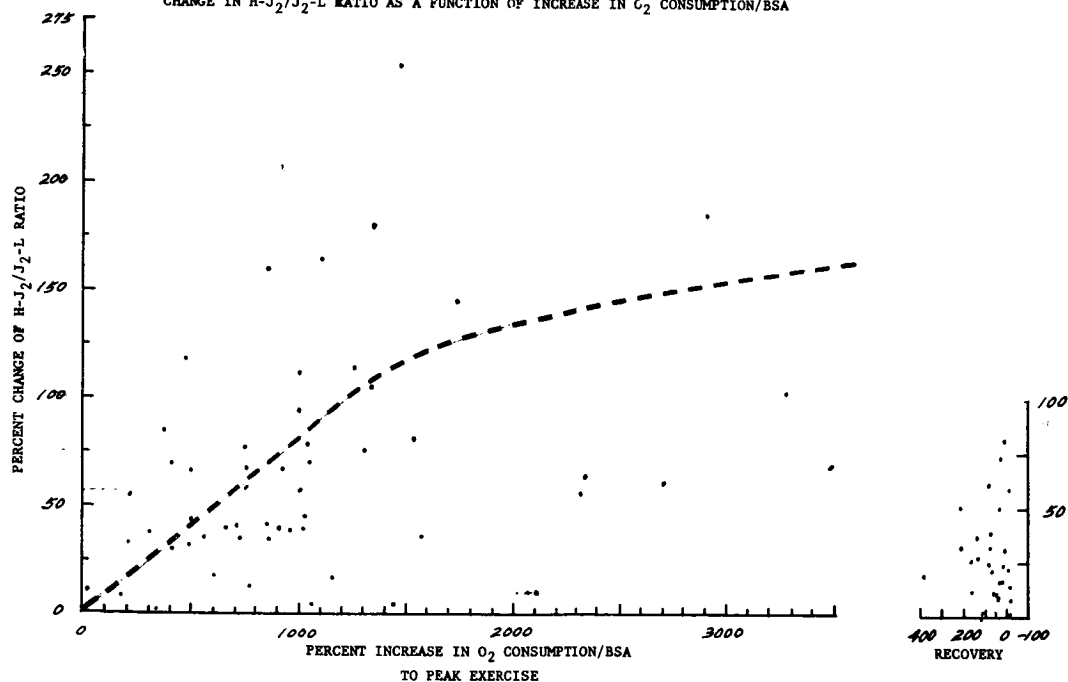


FIGURE 49-A  
TIME TENSION INDEX AS A FUNCTION OF  $O_2$  CONSUMPTION/BSA

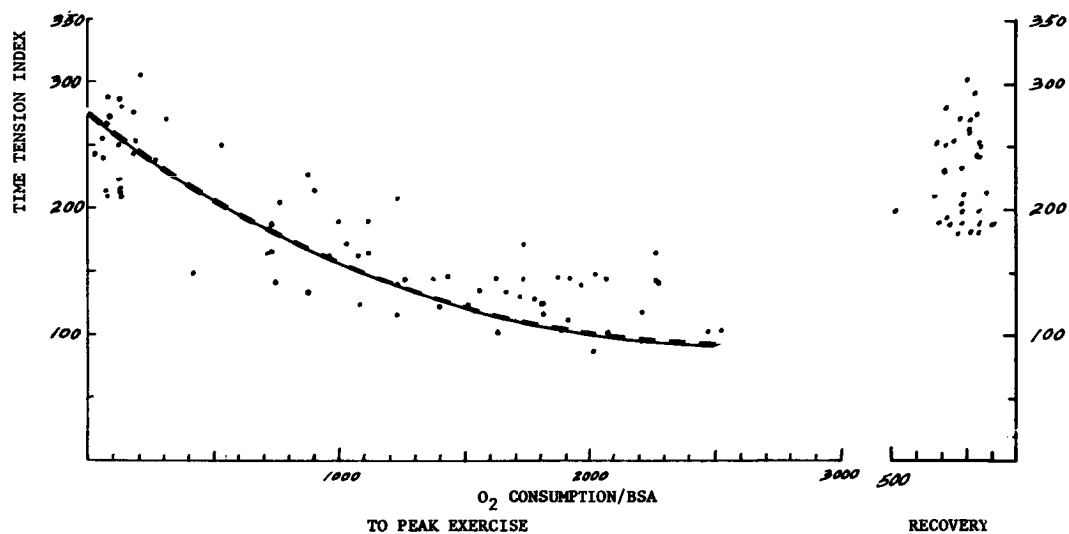


FIGURE 49-B  
CHANGE IN TIME TENSION INDEX AS A FUNCTION OF INCREASE IN  $O_2$  CONSUMPTION/BSA

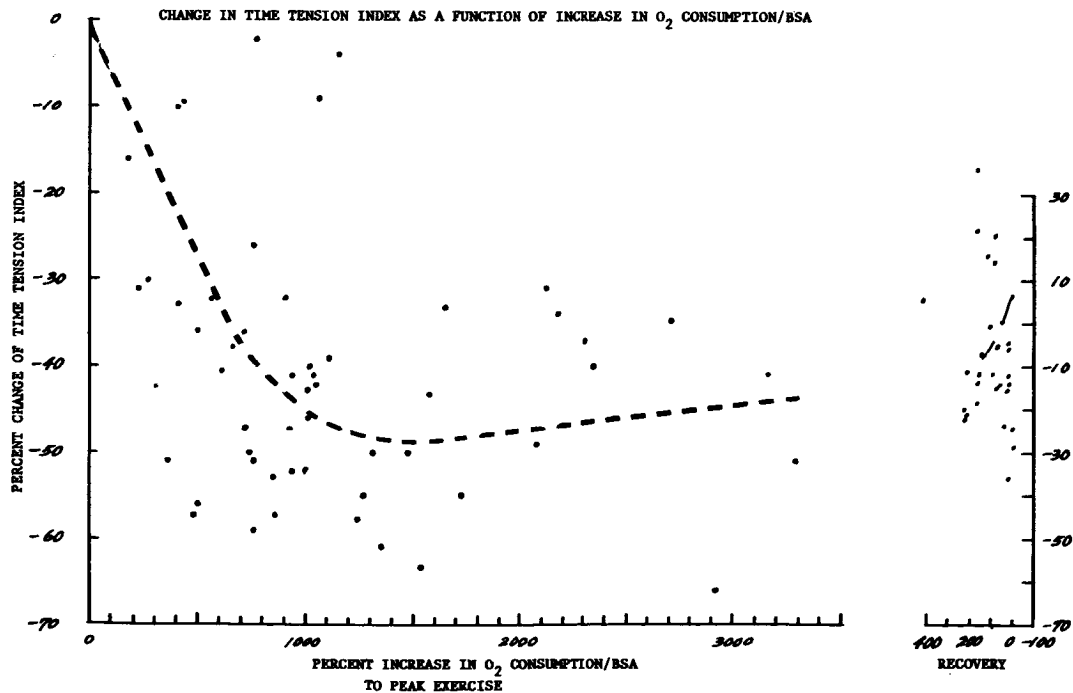


FIGURE 50-A  
MINUTE TIME TENSION RATE AS A FUNCTION OF  $O_2$  CONSUMPTION/BSA

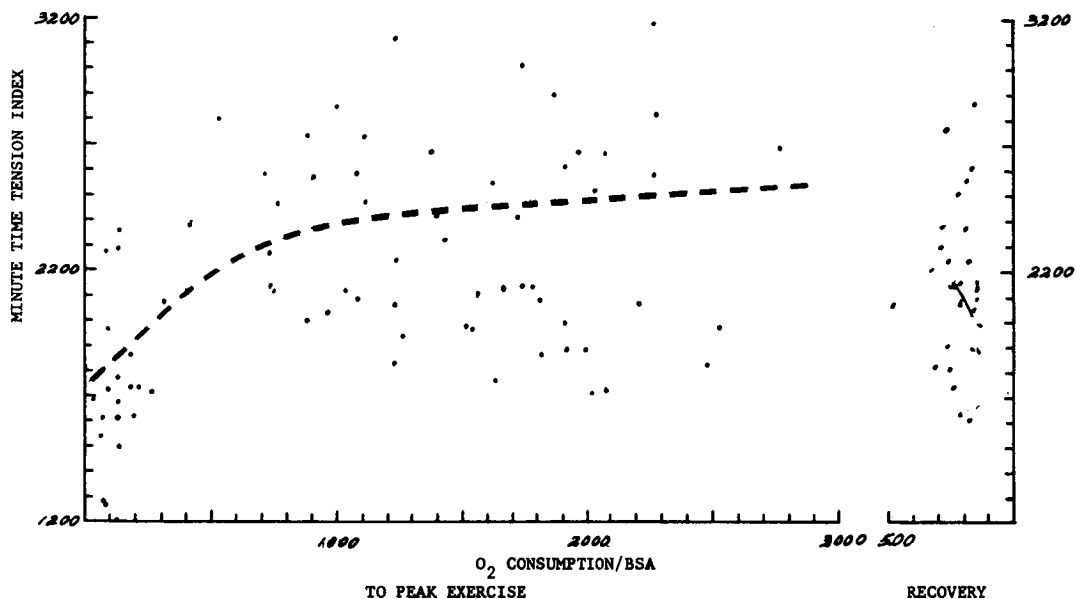


FIGURE 50-B  
CHANGE IN MINUTE TIME TENSION INDEX AS A FUNCTION OF INCREASE IN  $O_2$  CONSUMPTION/BSA

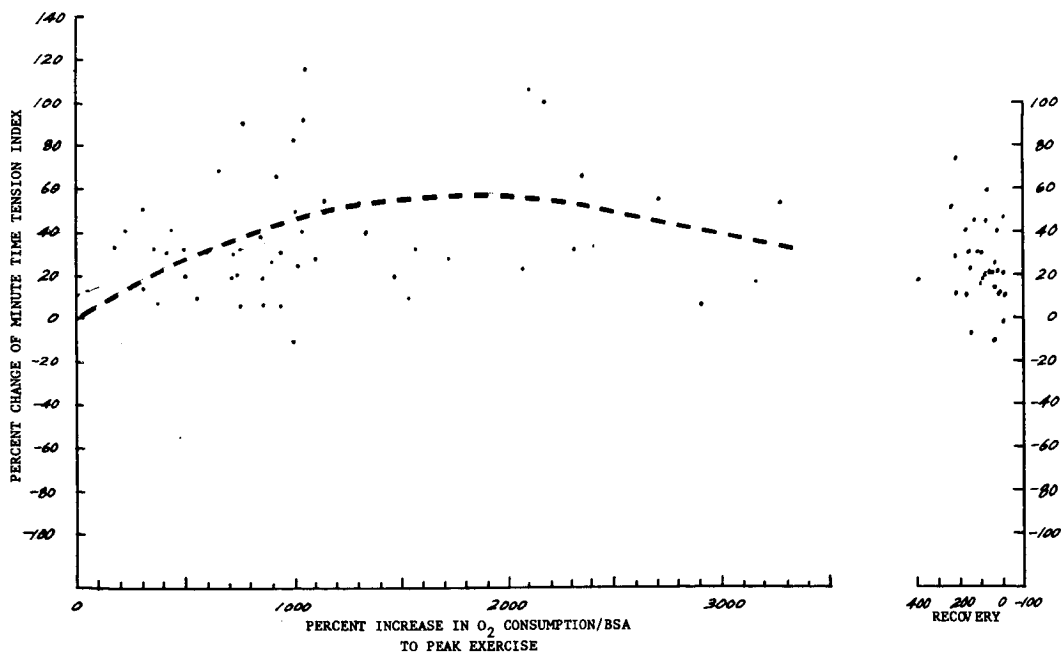




FIGURE 51-A  
VENT. SLOPE AS A FUNCTION OF  $O_2$  CONSUMPTION/BSA

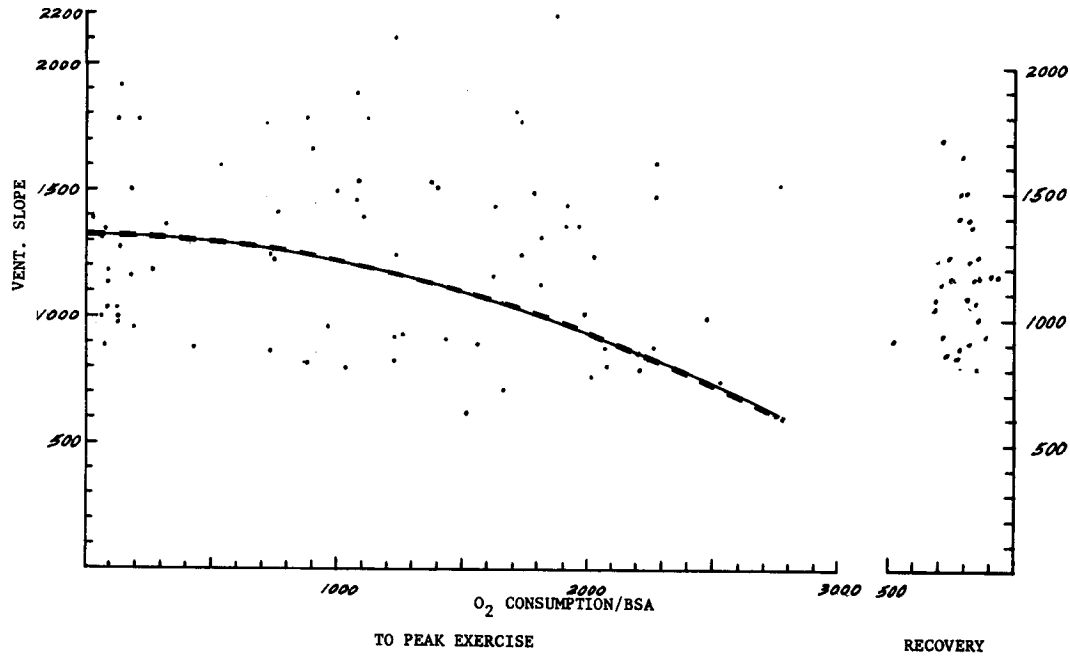


FIGURE 51-B  
CHANGE IN VENT. SLOPE AS A FUNCTION OF INCREASE IN  $O_2$  CONSUMPTION/BSA

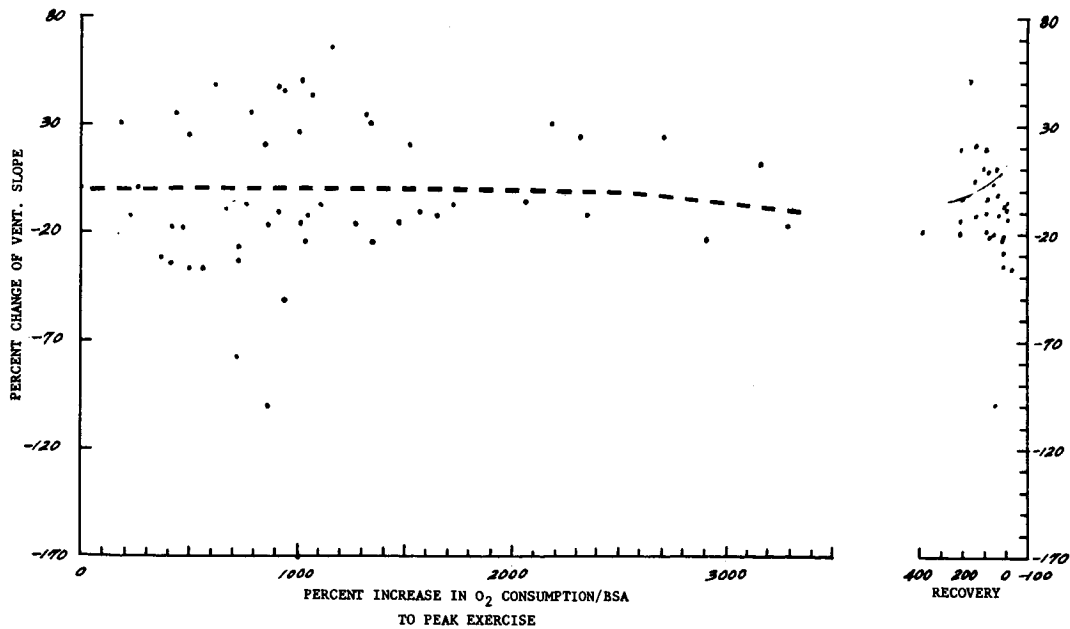


FIGURE 52-A  
MEAN SYSTOLIC EJECTION RATE AS A FUNCTION OF  $O_2$  CONSUMPTION/BSA

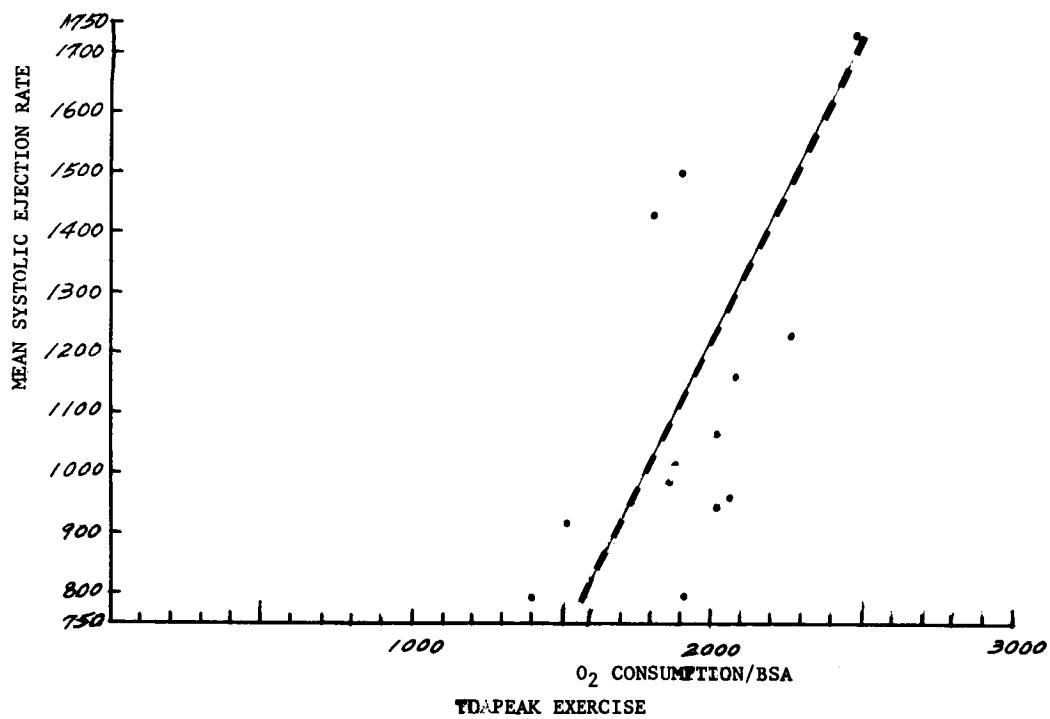




FIGURE 53-A  
PULSE PRESS X HEART RATE AS A FUNCTION OF  $O_2$  CONSUMPTION/BSA

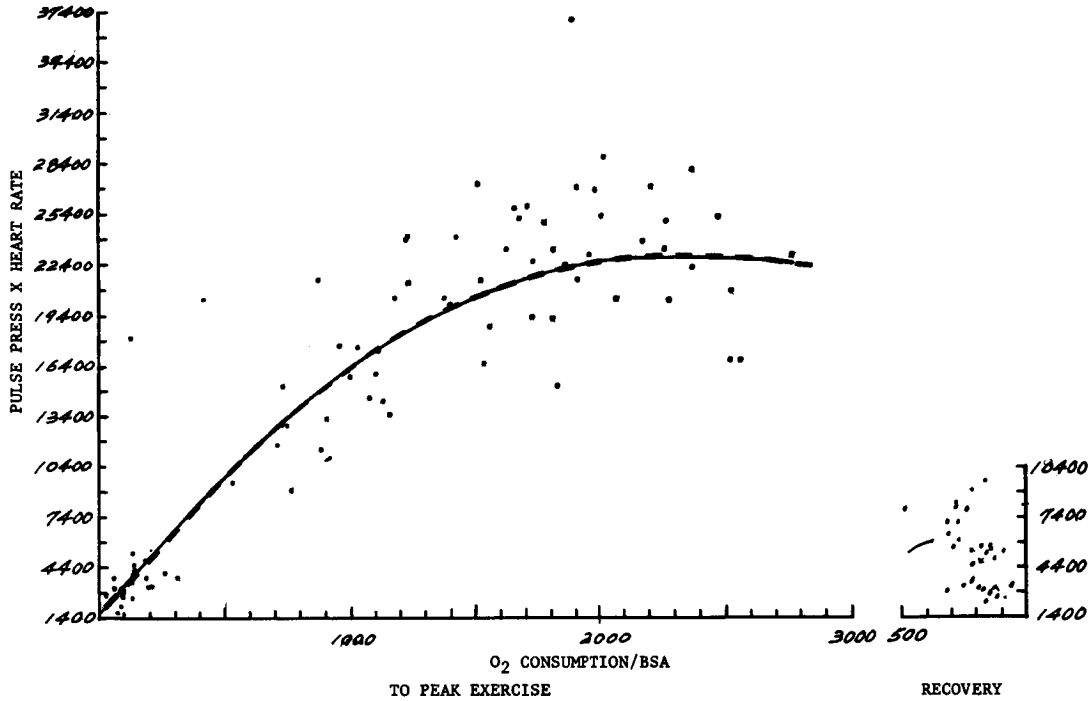
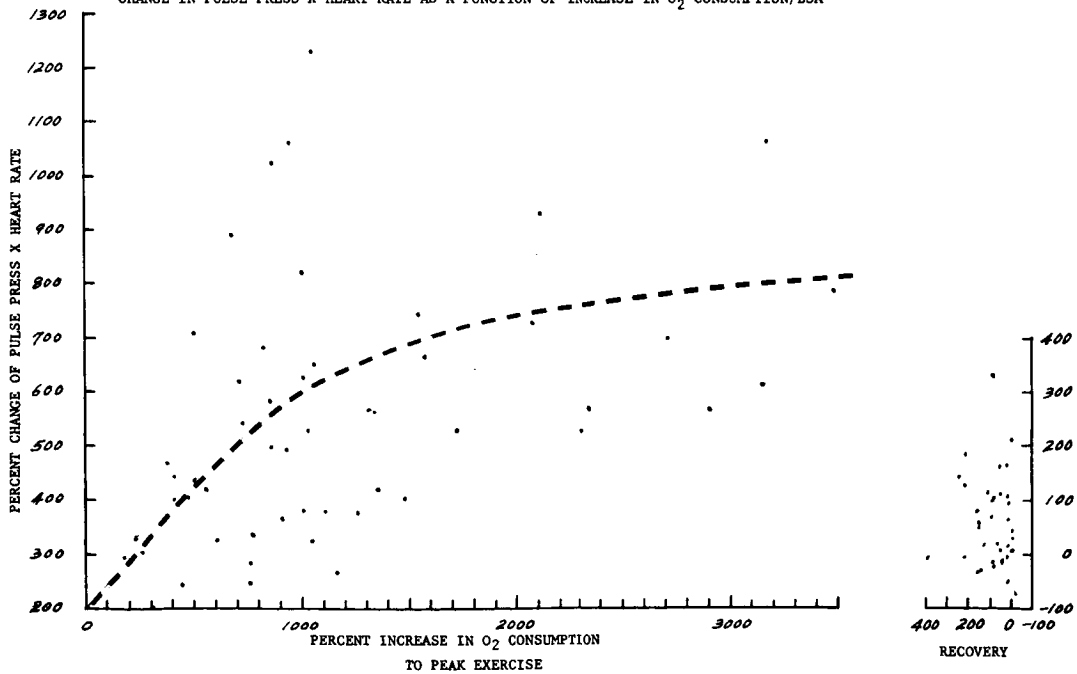




FIGURE 53-B  
CHANGE IN PULSE PRESS X HEART RATE AS A FUNCTION OF INCREASE IN  $O_2$  CONSUMPTION/BSA





peak exercise there were proportional increased in pulse rate, pulse pressure, and  $O_2$  consumption. Other observations are as follows:


- \* Figure 44A shows the relationship of Heart Rate to  $O_2$  consumption and Figure 44B relates the same data expressed as per cent change from the resting control. The  $O_2$  consumption increased in linear fashion as the heart rate increased.
- \* Figure 45A illustrates the relationship of pulse pressure to  $O_2$  consumption, and in Figure 45B this is expressed as per cent change. In the earlier stage of exercise, pulse pressure increases and then plateaus while  $O_2$  consumption continues to increase to the point of peak exercise.
- \* The vibrocardiographic intervals, "H-J<sub>2</sub>" (isometric contraction period) shown in Figures 46 A & B and "J<sub>2</sub>-L" (ejection period) in Figures 47 A & B were measured at rest and at each level of exercise and then compared with  $O_2$  consumption directly and then as per cent change.



The "H-J<sub>2</sub>" interval shortened slightly with increasing O<sub>2</sub> consumption. However there was a considerable scatter of values at higher exercise levels and no correlation could be made between isometric contraction time and oxygen consumption.

The "J<sub>2</sub>-L" intervals were widely scattered at resting levels but were uniformly shortened with increasing O<sub>2</sub> consumption at higher levels of exercise. The ejection time appeared to reach maximal shortening and began to plateau while oxygen consumption continued to increase as maximal exercise was achieved. (Figures 47 A & B)

- \* The ratio "H-J<sub>2</sub>/J<sub>2</sub>-L" was plotted against O<sub>2</sub> consumption, and again, as a per cent change. (Figures 48 A & B) This ratio is seen to increase linearly with increasing O<sub>2</sub> consumption, up to the point of maximal exercise. In these normal, athletic subjects the "H-J<sub>2</sub>/J<sub>2</sub>-L" ratio was found to increase even at levels of exercise in which the oxygen consumption reached ten times the resting control values.

- 
- \* The time tension index (per beat) showed a consistent shortening throughout exercise (Figures 49 A & B). The degree of shortening, however, was not proportional to the increase in  $O_2$  uptake, and, in five cases, reached a maximum value before peak oxygen consumption was obtained. The index returned to near control values at the first recovery record, irrespective of the oxygen uptake level reached at peak exercise.
  - \* The minute time tension index (Figures 50 A & B) increased in all but one subject throughout the initial levels of exercise, but again reached a plateau before peak oxygen uptake was achieved. All subjects achieved near control values at the first recovery record.
  - \* The ventricular slope had variable responses throughout exercise, some subjects showing an increase and some a decrease trend (Figures 51 A & B).

- \* The mean systolic ejection rate (Figure 52 A) showed good correlation with oxygen uptake. Only peak exercise values can be determined, however, because the Lamb formula is limited to the estimation of cardiac output at this exercise level.

Examination of the exercise data with regard to blood pressure and heart rate during exercise discloses an expected relationship to total oxygen consumption. The individual responses have been tabulated and charted. Oxygen uptake is linearly related to cardiac output and this cardiac output expresses itself by an increase in heart rate up to 3.5 times normal and an increase in pulse pressure from 2 to 3 times the control level.

A linear relationship existed between the work load (kpm/min) and the oxygen consumption corrected for body surface area. There was no correlation between age or height and total oxygen consumption. However, there is some degree of correlation between weight and oxygen consumption.


Pulse pressure times heart rate per minute ( $PP \times HR$ ) which is an indicator of cardiac output, showed a consistent increase throughout exercise (Figure 53 A & B). However, a plateau is reached before maximal oxygen consumption.

In the per cent change of these correlations, plateaus are seen earlier, at the level of 500-1000 per cent change of PP x HR and of 1000 per cent change of  $QO_2/BSA$ .

It is further contemplated to do correlative studies with standard methods for determining cardiac output. These studies are to be extended to include other stresses such as hypoxia, and are to be performed on patients with known heart disease.

#### 3.2.3.2 Summary

- \* Isometric and ejection time can be measured during vigorous exercise by an external technique, the vibrocardiogram.
- \* The duration of isometric contraction and ejection expressed as a ratio, parallel  $O_2$  consumption and the pulse rate.
- \* This external technique provides a useful method for evaluating myocardial function during exercise.

- 
- \* The TTI (per beat) response to exercise was a consistent shortening. The minute TTI consistently increased with exercise. Neither response was linear, both values reaching a plateau before maximal oxygen consumption.
  - \* The ventricular slope showed a variable response to exercise.
  - \* The relationships between oxygen consumption and blood pressure, heart rate, work load (kpm/min), BSA, height, weight, and age have been discussed.


#### 3.2.4 Vibrocardiographic Energy Studies

The measurement of the mechanical energy of cardiac contraction has shown promise of yielding an index of the functional capacity of the heart. Since no direct means of measuring this parameter in the human subject is available, the indirect approach of ballistocardiography, which measures the movement of the body in response to the contractile forces of the heart and the movement of blood through the arterial system, has been the only major technique employed. Utilizing an acceleration sensitive system, the acceleration of the body is multiplied by its mass to provide a force measurement for any time period in

the cardiac cycle. Similarly, knowing the distance which the body was displaced for the given force and the time required for these motions, cardiac work and power measurements can be obtained.

Although ballistocardiographic methods have been shown to indicate disease states, differentiation between abnormalities of the heart and the arterial tree cannot be obtained, because the elastance of the arterial system plays an important role in the genesis of total body motions. Ballistocardiographic studies on the response of the circulatory system to stresses have also been limited as the technique requires a fixed subject position.

The measurement of precordial motions obviates some of the disadvantages of total body ballistocardiography but introduces several new variables. Vibrocardiographic recordings can be made during stress procedures but, since the transducer measures displacements of a small portion of the precordium instead of the whole body, as in ballistocardiography, the mass of the system being moved is an unknown. However, since this mass value is a constant in any individual, relative changes in force measurements can be derived from the vibrocardiogram. The method used in assessing vibrational energy from the vibrocardiogram makes



use of the Kinetic Energy formula,  $KE = 1/2 MV^2$  where M is equal to the mass of the body and V is equal to its velocity. Since the vibrocardiographic waves are sinusoidal and of relatively the same frequency under resting and stress conditions, changes in displacement (amplitude) are a direct function of velocity. The square of the amplitude of vibrocardiographic waves may then be substituted for  $V^2$  in the above formula. Since the mass of the body is a constant, kinetic energy of the vibrocardiogram is proportional to the square of the displacement.

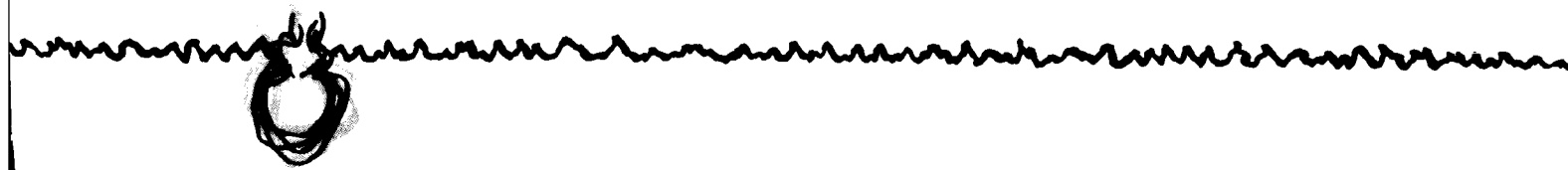
Two forms of experimentation have been thus far attempted in an effort to relate vibrocardiographic energy measurements to cardiac energy. The first involved the correlation of vibrocardiographic data with ballistocardiographic energy measurements in response to exercise. The second form of experimentation involved a study of the relationship of VbCG energy to oxygen uptake in subjects during maximal exercise. These studies are discussed below.

#### 3.2.4.1 Correlation of Vibrocardiogram with Ballistocardiogram

Through the efforts of Dr. Richard Brenneman and Dr. Marvin Abramovitz of NASA's Western Operations Office in Los Angeles, permission was obtained to utilize the ballistocardiographic facilities of the Lovelace Foundation and Pensacola Naval Air Station for the purpose of performing simultaneous

ballistocardiographic and vibrocardiographic studies. One member of our staff then visited these laboratories to obtain simultaneous recordings of VbCG and ballistocardiograms under resting and exercise conditions. The results of these studies are listed below under the laboratories from which they were obtained.

Lovelace Foundation: Three experiments were performed at this laboratory with the cooperation of Dr. Robert Proper and Dr. Thomas Nevison. The instrumentation included a Schwartz ultra low frequency critically damped table, the standard vibrocardiographic transducer, and an E/M photographic recorder. Simultaneous recordings of the head to foot displacement, velocity, and acceleration BCG along with the VbCG and ECG were then obtained at rest and following a five minute period of exercise on a bicycle ergometer (3 KP load). VbCG's and BCG's were then analyzed by comparing the areas under the squared curves at rest and after exercise. The magnitude and direction of change encountered after exercise was similar for both the VbCG and BCG.



Pensacola Naval Air Station: Four experiments were performed in this laboratory with the cooperation of Dr. Robert Morse. The instrumentation consisted of a Nickerson ultra-low frequency acceleration ballistocardiographic table, the VbCG, and a Sanborn pen recorder. Recordings were obtained of the head to foot acceleration BCG, VbCG and ECG, at rest and following exercise on a bicycle ergometer. The methods of analysis of these data were the same as in the Lovelace study and the changes in the curves after exercise were essentially the same as those found in the previously mentioned study.

In addition to the above mentioned studies, much useful data has been supplied by Drs. Nevison and Proper of the Lovelace Foundation. This group has utilized the VbCG as an additional physiologic monitoring parameter in their altitude chamber and zero-G flight studies. Copies of the data which they obtained from their studies were made available to us and will be reported on, once these analyses are complete. Preliminary illustration of the data are shown in Figure 54.

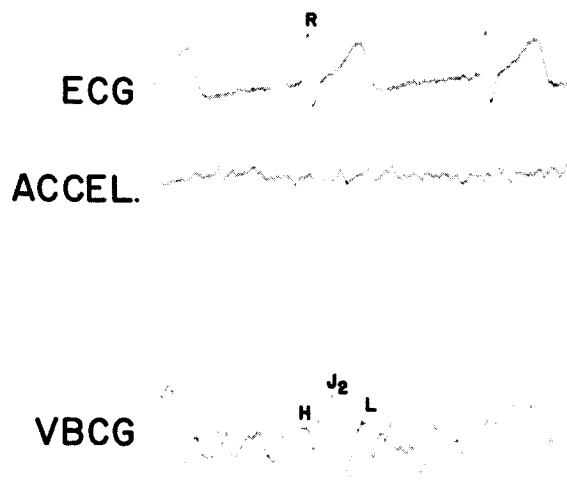


Figure 54

Dr. Proper has also indicated that he may utilize the VbCG in his physiologic aging study program. This study would be of great interest to us as it includes ballistocardiographic and cardiac output data obtained by the radioactive iodine

technique, and would provide additional correlative data between the VbCG and stroke volume in the human subject.

Dr. Morse of the Pensacola Naval Air Station has also shown interest in the VbCG and intends to incorporate this technique in his ballistocardiographic screening of normal male subjects. These data would be most valuable as it would include a great number of normal subjects in a wide range of age groups. It also provides data for correlating ballistocardiographic abnormalities with vibrocardiographic alterations.

#### 3.2.4.2 VbCG Energy Studies on Athletes at Maximal Exercise

Vibrocardiographic energy measurements were obtained from athletes at various levels of exercise. Using the energy values for each subject at rest (control), normalized

quantities can be obtained for all other levels of stress expressed as a ratio between energy level at stress and that individual's control energy level. These ratios or normalized values can then be compared to data similarly gathered for other subjects.

Figure 55 represents preliminary effort to display the increase in total energy during systole that takes place

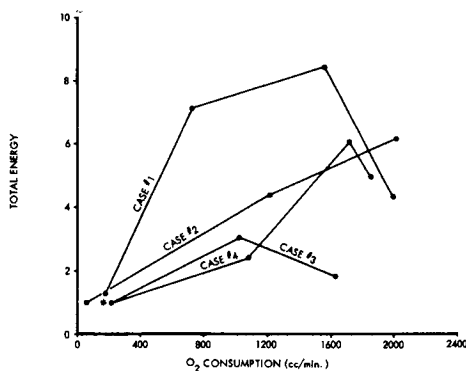


Figure 55

in the VbCG of athletes under strenuous exercise. All curves start from the normalized control energy level of units and the particular subject's level of oxygen consumption at control. As indicated the energy level increases by large factors during exercise. It returns to control levels after 5 to 15 minutes of rest.

Figure 56, also in preliminary form, indicates changes during stress of the ratio of VbCG energy during isometric contraction and ejection phase of systole. This figure

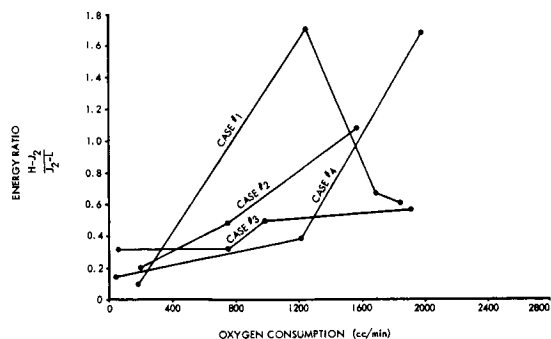


Figure 56

also shows an increase in the ratio with greater stress, demonstrating that proportionately greater energy is being developed during isometric contraction than ejection even though both are increasing many times as indicated by the previous figure.

While this study is at a very early stage of development and covers only a few healthy athletes, the ultimate intention is to compare athletes, healthy normals, and known cardiac abnormals to determine if an index can be found in the VbCG output to indicate abnormals from normals and hopefully indicate at an early stage stresses induced by hypoxia, hypercapnia, etc.

### 3.2.5 Human Hypoxia Studies

The effects of hypoxia on the VbCG have been studied in several volunteer subjects. The spirometer technique was used for induction of hypoxia, and the subjects rebreathed for periods ranging from three to seven minutes, with vibrocardiograms and electrocardiograms recorded at thirty second intervals. Vibrocardiographic energy data

throughout successive levels of hypoxia are shown in Figure 57. Although these studies are too preliminary to

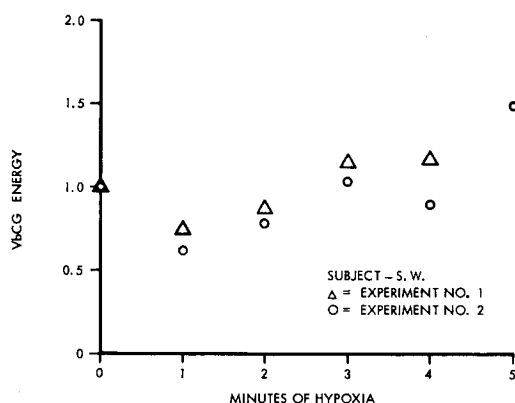


Figure 57

justify any conclusions, it is apparent that vibrocardiographic alterations occur at a very early level of hypoxia. More definitive studies utilizing blood oxygen measuring equipment are now planned.

### 3.3 Exhibits, Publications and Presentations at Scientific Meetings

The exhibits, publications and presentations listed below have been experienced thus far under NASA Research Grant N<sub>S</sub>G-289-62.


#### Exhibits

1. IV World Congress of Cardiology, Mexico City, Mexico October 7-13, 1962.  
"Modern Technics and Applications of Precordial Movements".
2. Aerospace Medical Association, Los Angeles, California, April 29-May 2, 1963.  
"Cardiac Vibrations".

3. American College of Cardiology, Los Angeles, California, February 27-March 3, 1963.  
"The Relationship of Pre-Ejection Contraction Time to Ejection Time as an Index of Myocardial Function: Vibrocardiographic Correlations".


#### Publications

1. Use of the vibrocardiogram for the detection of heart disease. The Teachine Rounds, Part III, (Journal of the Wadsworth General Hospital) 5:285-296, August, 1962.
2. Measurement of Isometric contraction and ejection time by the vibrocardiogram. Am. J. of Cardiology (In press)
3. Common origin of precordial vibrations. Am. J. of Cardiology (In press)  
Clinical Research (Abstract) 11:100, Jan. 1963.
4. Thoracic transfer of cardiac energy. Proceedings of the San Diego Symposium for Biomedical Engineering. 3:24-25, 1963.
5. Study of the vibrocardiogram on athletes during maximum exercise. The Physiologist (Abstract) August 1963.
6. Correlation of the vibrocardiogram with the hemodynamic events of the cardiac cycle in the dog. (Abstract) The Physiologist August 1963.

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7. Correlation of vibrocardiogram with events of the cardiac cycle. I. Normal dogs. (Submitted for publication to Circulation Research)
  8. Maximum exercise in athletes. (In preparation)
  9. Correlation of the exercise vibrocardiogram and exercise electrocardiogram with the functional status of normal humans and patients. (In preparation)
  10. Maximal exercise testing. (In preparation)
  11. Study of vibrocardiographic alterations over the precordium. (Submitted for publication to Aerospace Medicine)

#### Presentations at Scientific Meetings

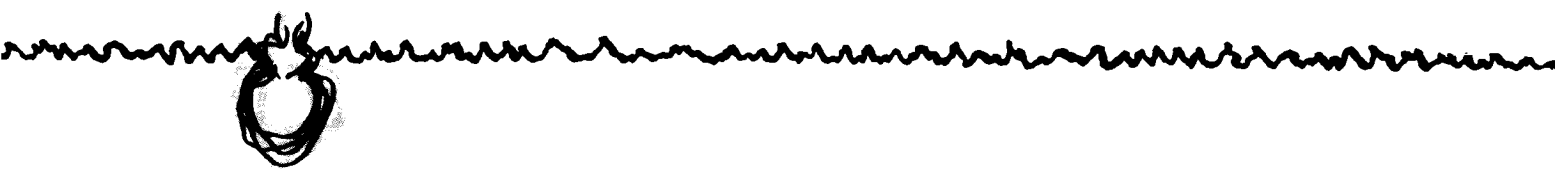
1. Western Society for Clinical Research, February 2, 1963. "The Common Origin of Precordial Vibrations" (Carmel, California)
2. Regional Meeting of the American College of Physicians, February 15-17, 1963. "Measurement of Pre-ejection and Ejection Contraction Time by the Vibrocardiogram". (Coronado, California)
3. San Diego Symposium for Biomedical Engineering, April 22-24, 1963, "The Common Origin of Precordial Vibrations". (San Diego, California)
4. Aerospace Medical Association Pan Pacific Symposium on Aerospace Medicine, May 5-8, 1963. "The Vibrocardiogram as a Heart Monitor". (Honolulu, Hawaii)

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5. The American Physiological Society, August 27-30, 1963,  
"Correlation of the Vibrocardiogram with the  
Hemodynamic Events of the Cardiac Cycle in the Dog".  
"Study of the Vibrocardiogram on Athletes during  
Maximum Exercise". (Coral Gables, Florida)

### 3.4 Bibliography


The bibliography presented in this section is directly concerned with the material presented in the preceeding sections.


One of the special projects undertaken by our Research Staff during the past few months was that of compiling a bibliography which includes all available publications in the fields of precordial vibration recording and ballistocardiography. Copies of this complete bibliography are available upon request.




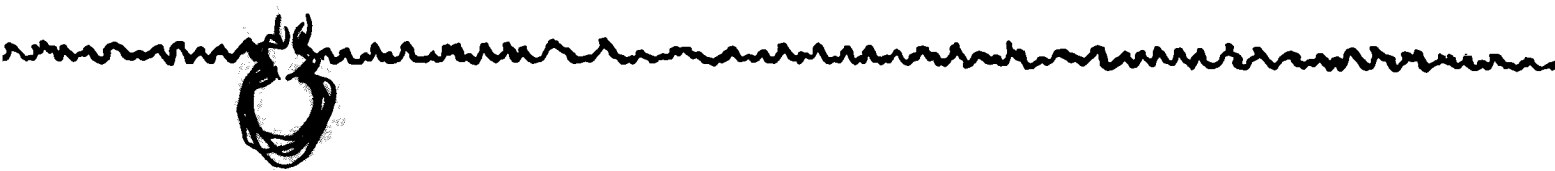
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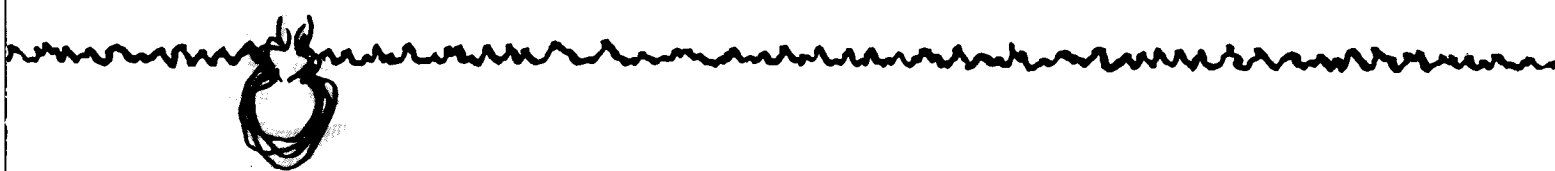
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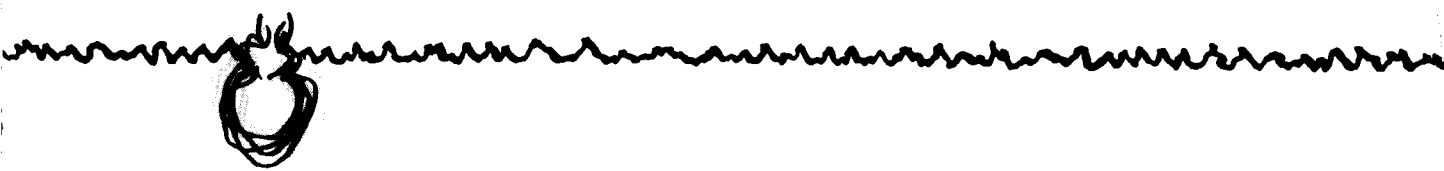
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